Multi-messenger studies with the Pierre Auger Observatory

Lorenzo Perrone[1,2] for the Pierre Auger Collaboration

[1] Università del Salento and INFN Lecce
[2] Pierre Auger Observatory, Malargue, Argentina

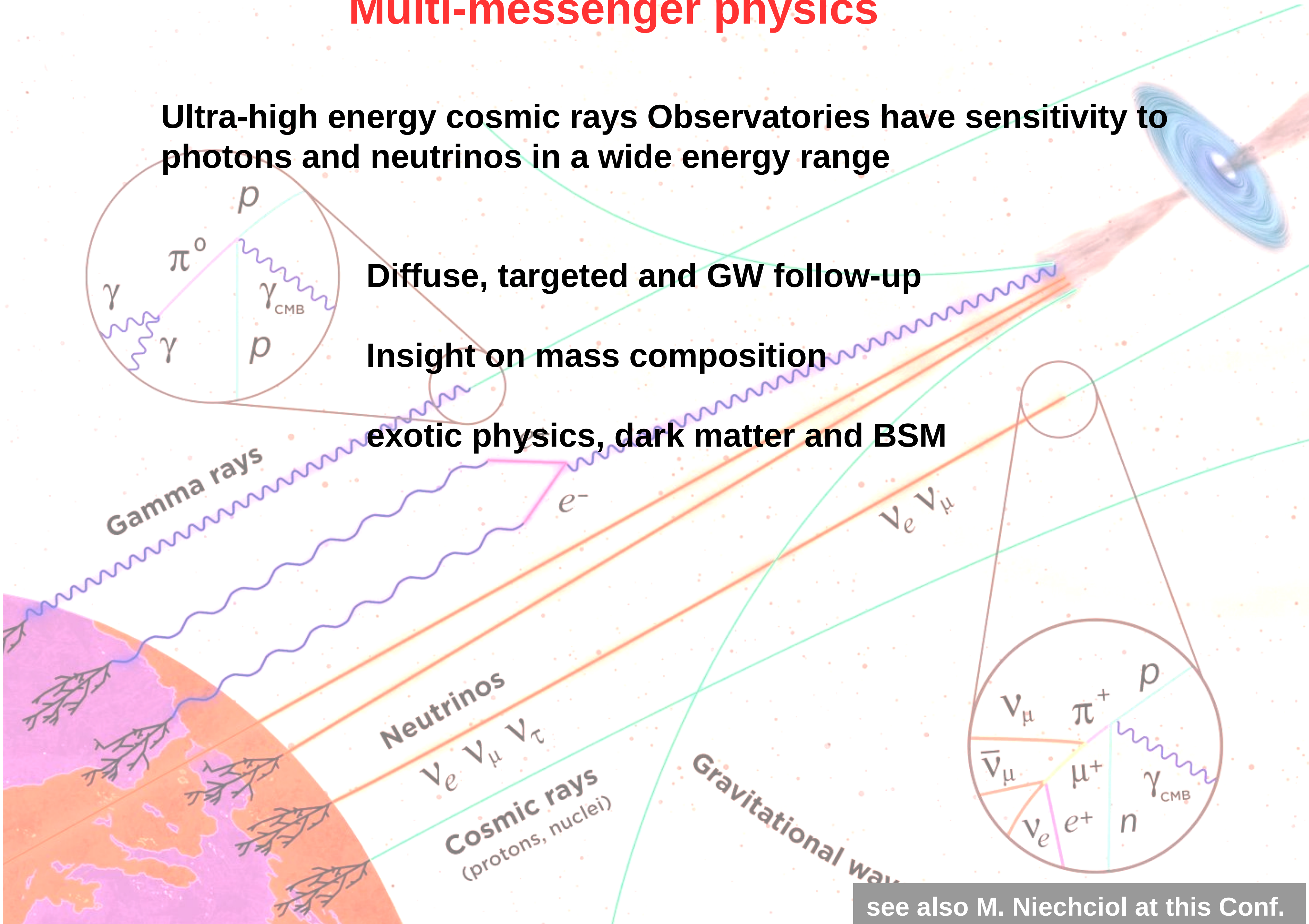
Multi-messenger physics

Ultra-high energy cosmic rays Observatories have sensitivity to photons and neutrinos in a wide energy range

Diffuse, targeted and GW follow-up

Insight on mass composition

exotic physics, dark matter and BSM



see also M. Niechciol at this Conf.

The Pierre Auger Observatory

~ 400 members, 17 countries

3000 km^2

Surface detector

array of 1660 Cherenkov stations on a
1.5 km hexagonal grid of 3000 km^2
Dense sub-array (750 m) of 24 km^2

Fluorescence detector

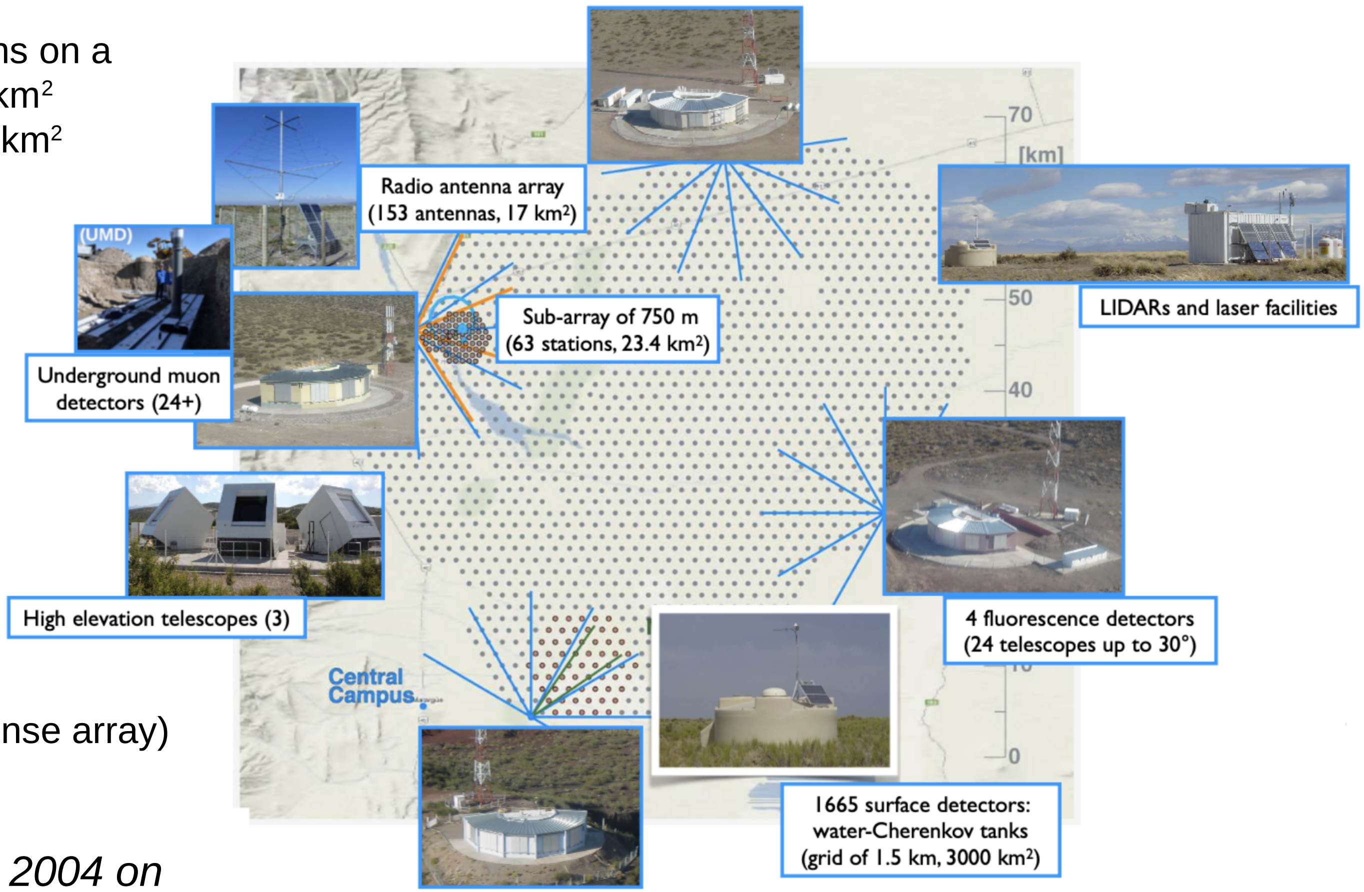
4+1 buildings overlooking the array (24 + 3 HEAT telescopes)

Radio detector

153 Radio Antenna → AERA

Muon Detectors

Buried scintillators (region of dense array)

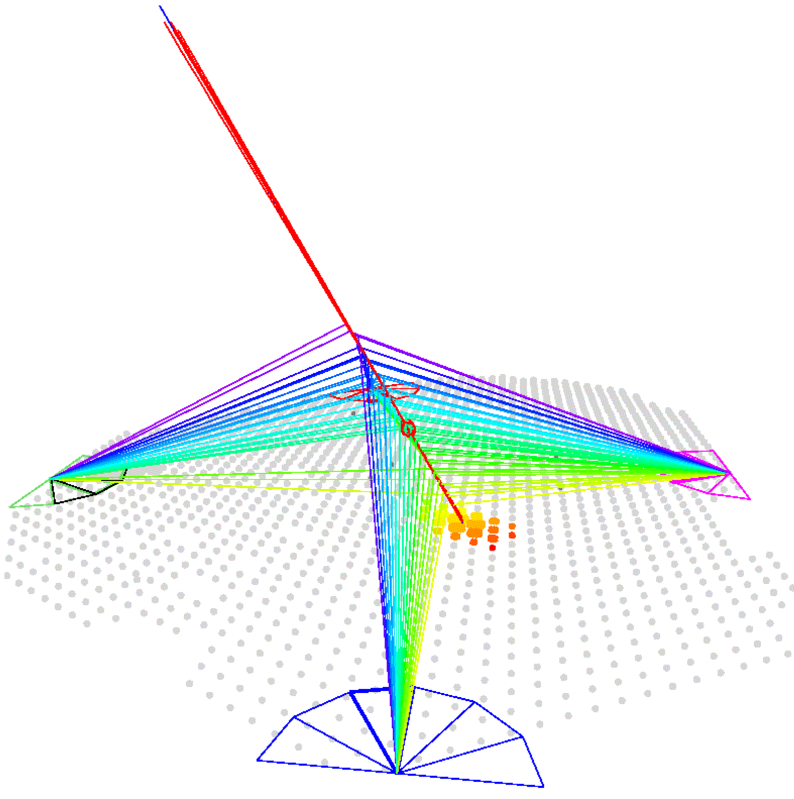


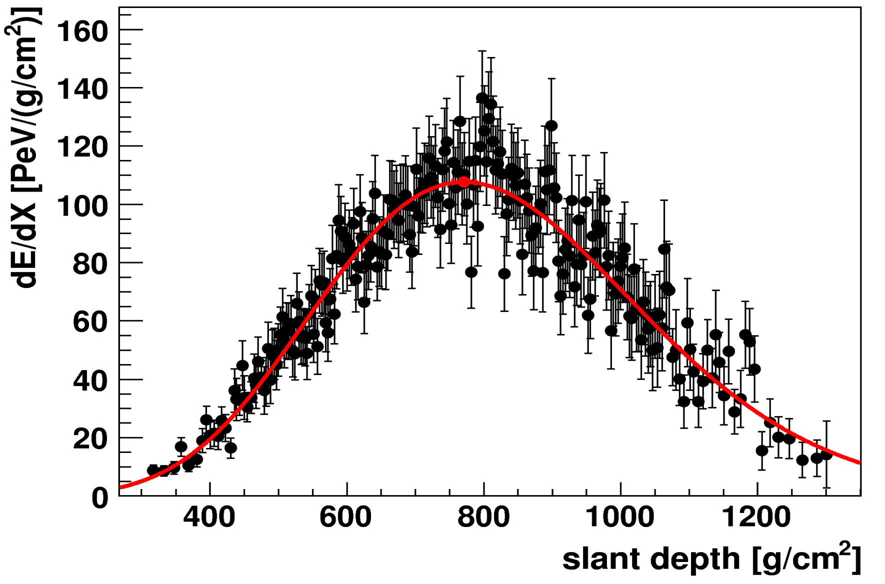
***Phase 1** : data taking from 2004 on*
(from 2008 with the full array in operation):

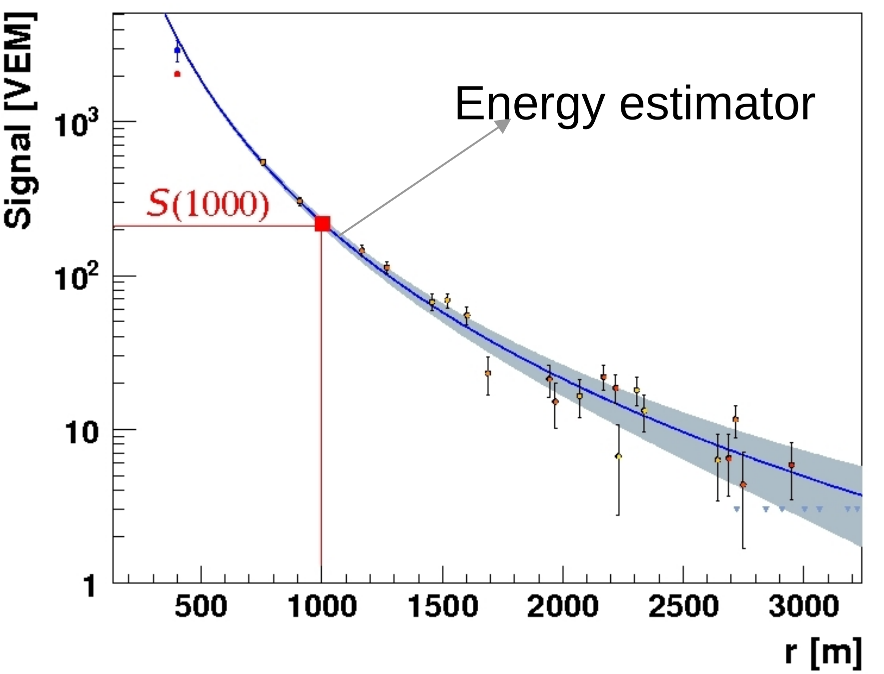
- Over 120.000 km^2 sr yr for anisotropy studies
- Over 90.000 km^2 sr yr for spectrum studies

Phase 2 - the AugerPrime upgrade
Data taking from 2023 to 2030…
Multiple detectors

The Hybrid paradigm







Longitudinal profile

FD - calorimetric measurement

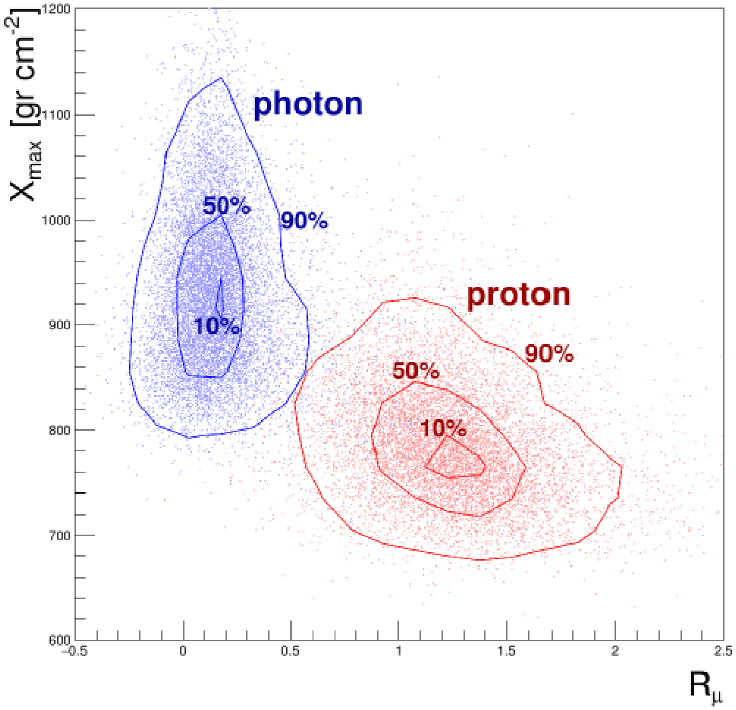
- duty cycle 15%

Density of particles at the ground

SD - duty cycle ~ 100%

Use the energy scale provided by FD to calibrate the entire SD data sample

Search for primary photons



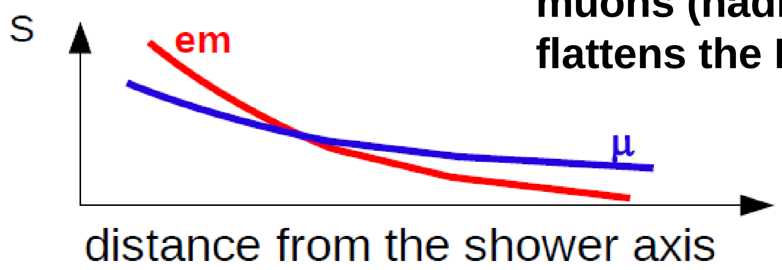
Photon showers develop deeper in the atmosphere and have less muons

Photon signature

FD → deeper Xmax

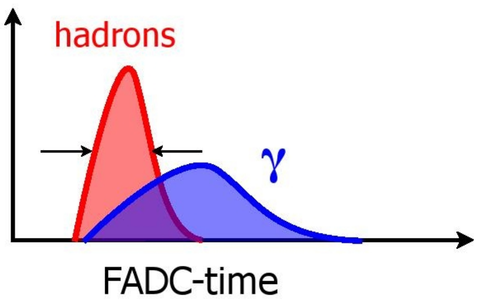
SD → steeper LDF, broader signal

steeper LDF



Higher fraction of muons (hadrons) flattens the LDF

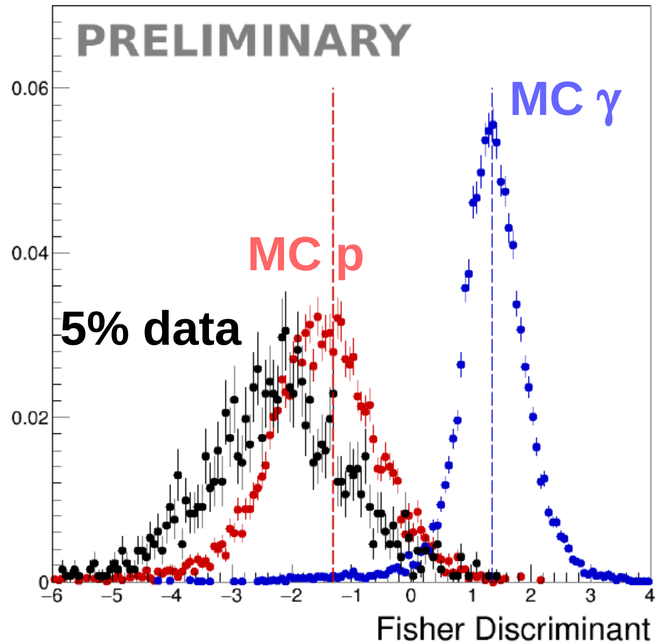
longer rise-time



Muons are produced higher in the atmosphere and arrive within a shorter time

Hybrid and SD photon search

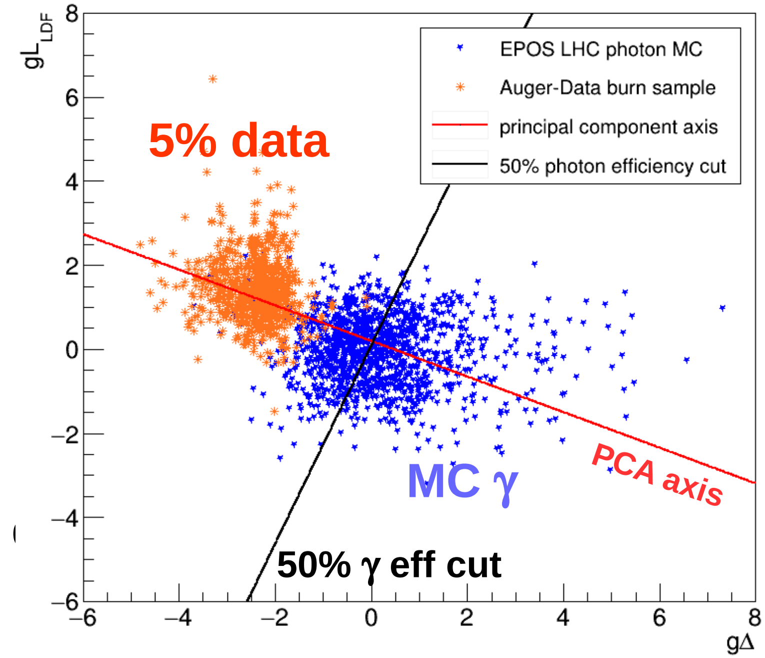
Hybrid selection: Fisher response



Maximum of shower development: $\mathbf{X_{max}}$

Muon content of the shower (universality): F_{μ}

SD selection: PCA transformed



Deviation from data <LDF>: $\mathbf{gL_{LDF}}$

rise-time rel. event-wise quantity: $\mathbf{g_{\Delta}}$

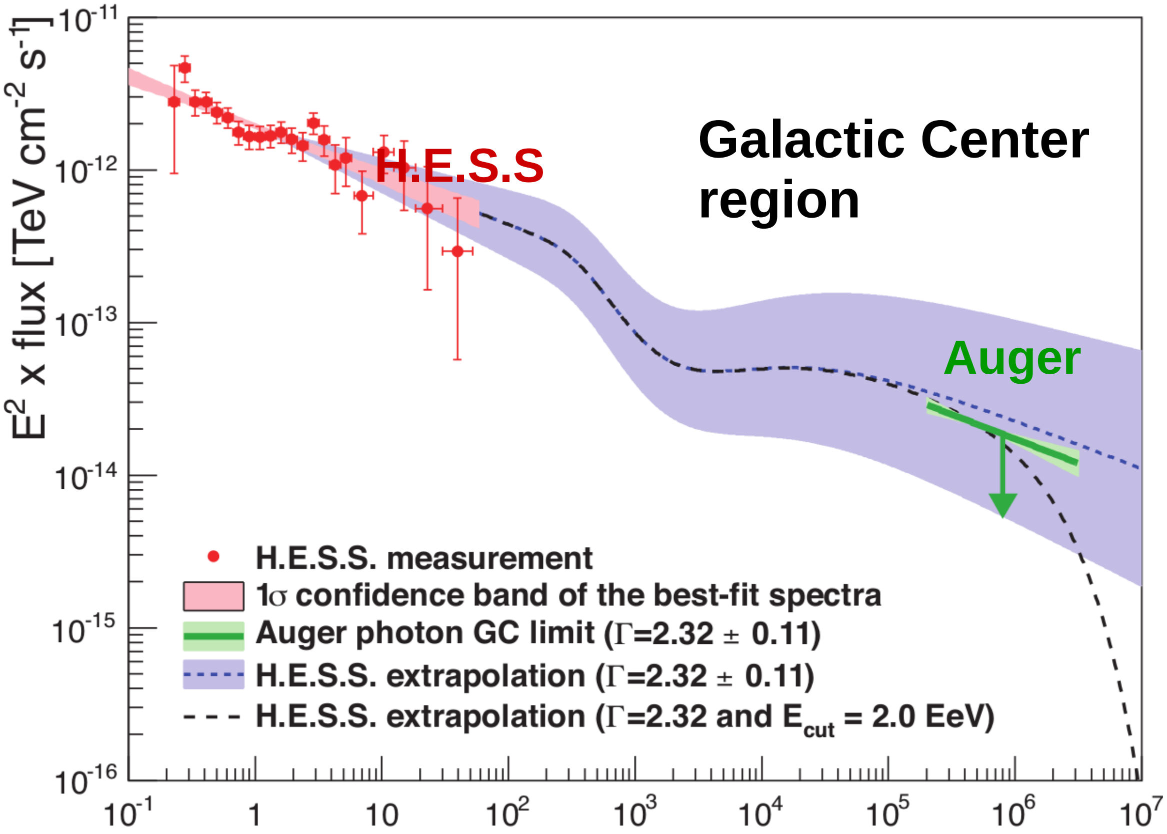
Diffuse search → strictest limits at E> 0.2 EeV

M. Niechciol at this Conf.

- Top-down model disfavored
- CR proton dominated scenario (also the most pessimistic cases) disfavoured
- Constraining mass and lifetime of dark matter particles
- Auger Phase II: additional information for better photon/hadron separation or photon discovery

Targeted photon searches

Pierre Auger Coll., ApJL 837: L25 (2017)



extrapolated flux (conservative)

- focus on **12 target sets** (364 candidates sources)
- stacked analysis

→ complement targeted neutron searches

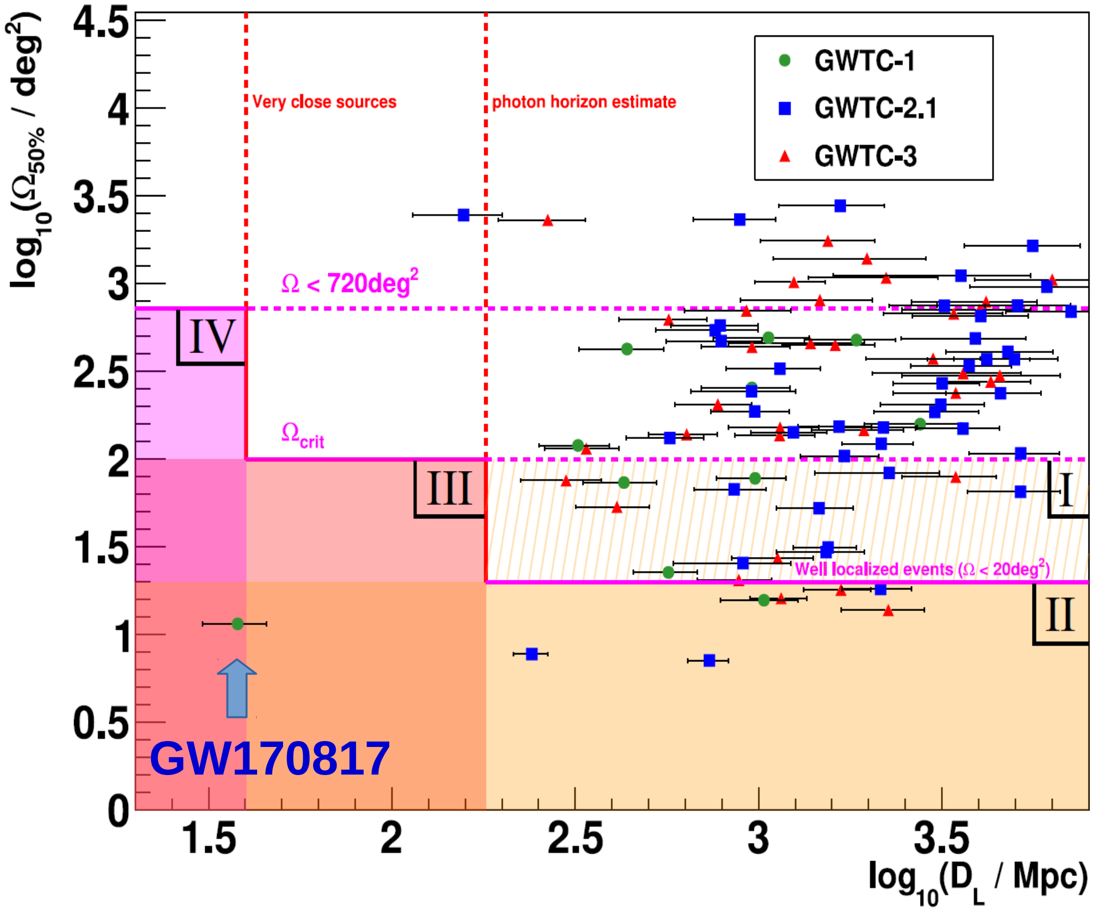
NO evidence for *nearby* photon-emitting *steady* sources in the EeV range

→ PS limits constrain the continuation of measured TeV fluxes to EeV energies

GW follow-up (stacked): γ searches

Search for time-directional coincidence with 91 GW events from LIGO/Virgo

Four “classes” inspected
→ based on localization, quality, distance and time window



$(D_\mathrm{L} < \infty$	and	$\Omega_{50\%} < 100\,\mathrm{deg}^2)_\mathrm{short}$	“class I”
$(D_\mathrm{L} < \infty$	and	$\Omega_{50\%} < 20\,\mathrm{deg}^2)_\mathrm{long}$	“class II”
$(D_\mathrm{L} < 180\,\mathrm{Mpc}$	and	$\Omega_{50\%} < 100\,\mathrm{deg}^2)_\mathrm{long}$	“class III”
$(D_\mathrm{L} < 40\,\mathrm{Mpc}$	and	$\Omega_{50\%} < 720\,\mathrm{deg}^2)_\mathrm{long,short}$	“class IV”.

short: Δt = 1000 s t_0= -500 s
long: Δt = 1d t_0=+500 s

Selected: 3 in class I
7 in class II

GW170817 ~ 40 Mpc
→ within the photon horizon

PoS(ICRC2021)973, paper in preparation

Any distance: test for new physics !

GW follow-up (stacked): fluence UL

E > 10 EeV, 6T5 events, 30° < zenith < 60°, efficiency 50% cut (Fisher discriminant)

No candidates found for any of the GW events inspected

Flux upper limits → $\frac{d\Phi_\gamma^{GW}}{dE_\gamma}(E_\gamma) = k_\gamma E_\gamma^\alpha$ → $k_\gamma^{UL} = \frac{N_\gamma^{UL}}{\int_{E_0}^{E_1} dE_\gamma E_\gamma^\alpha \mathcal{E}(E_\gamma, \theta_{GW}, \Delta t)}$

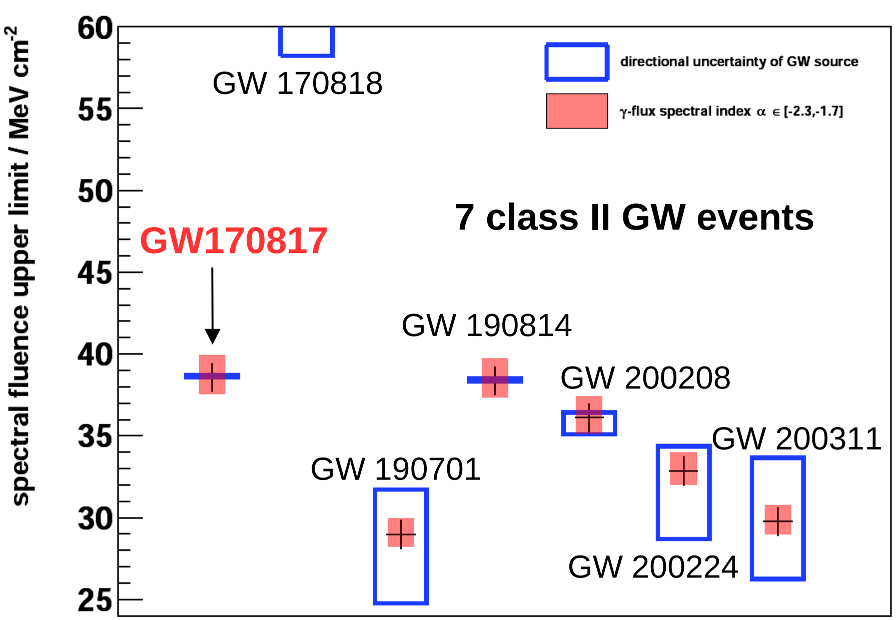
Constraining photon emission of GW170817 in the UHE range!

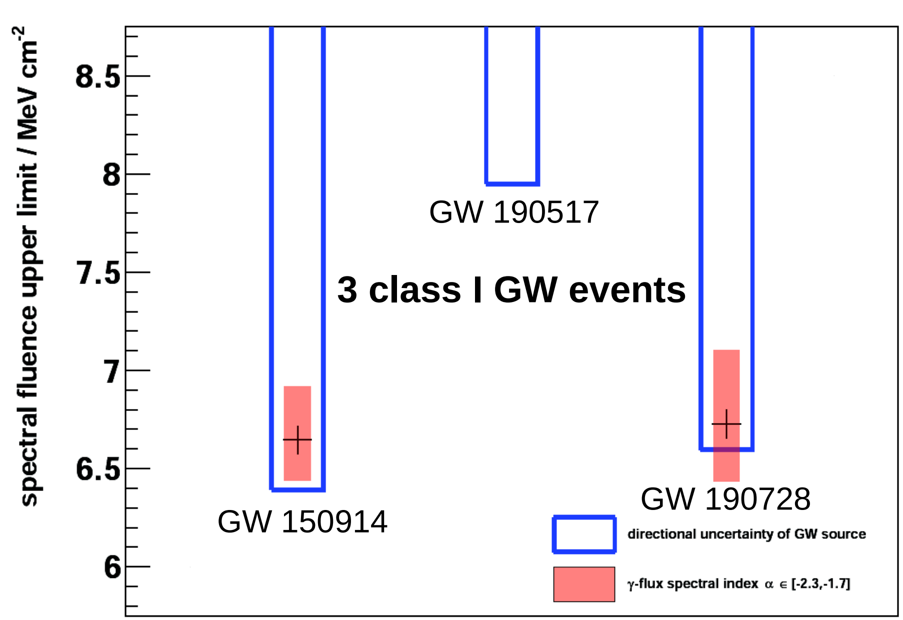
$$\mathcal{F}_\gamma^{UL} = \int_{t_0}^{t_1}\int_{E_0}^{E_1} dt\, dE_\gamma\ E_\gamma\ \frac{d\Phi_\gamma^{GW}}{dE_\gamma}$$

t_0, t_1 time window

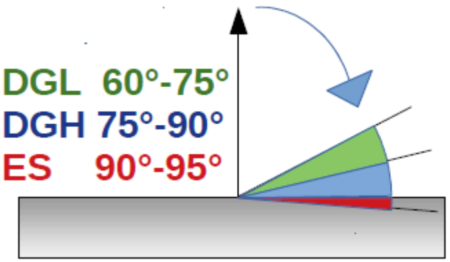
$E_0=10^{19}$ eV $E_1=10^{20.5}$eV

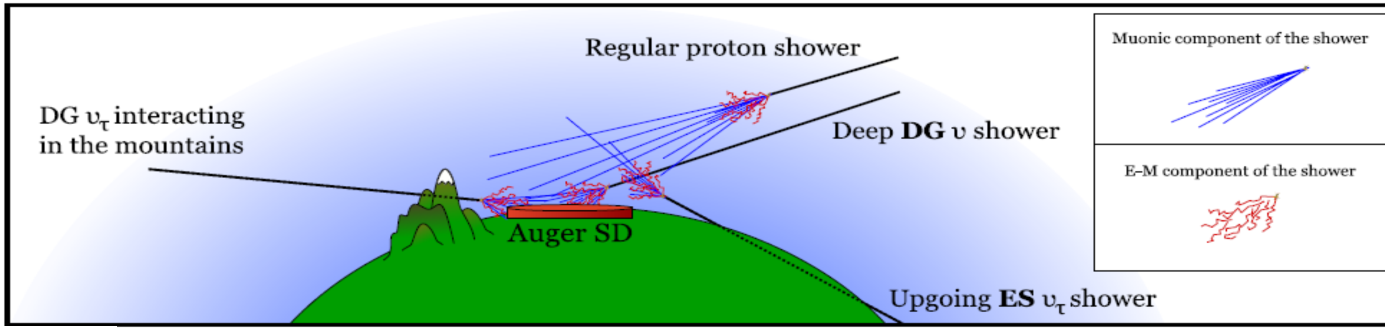
$\mathcal{E}$ directional exposure

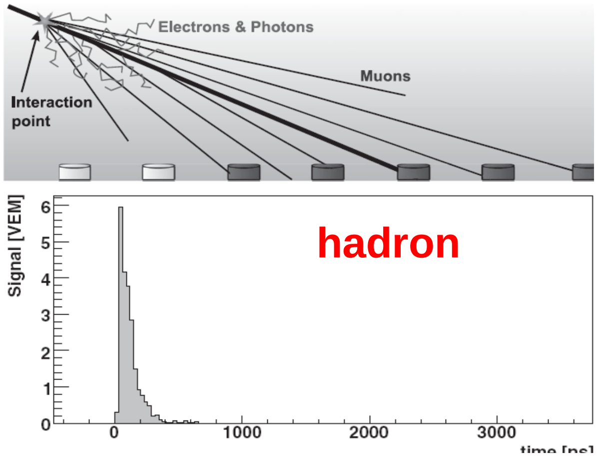


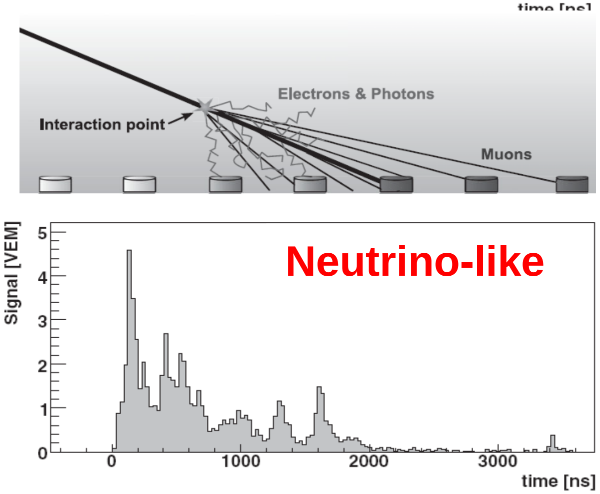


UHE neutrinos with the SD

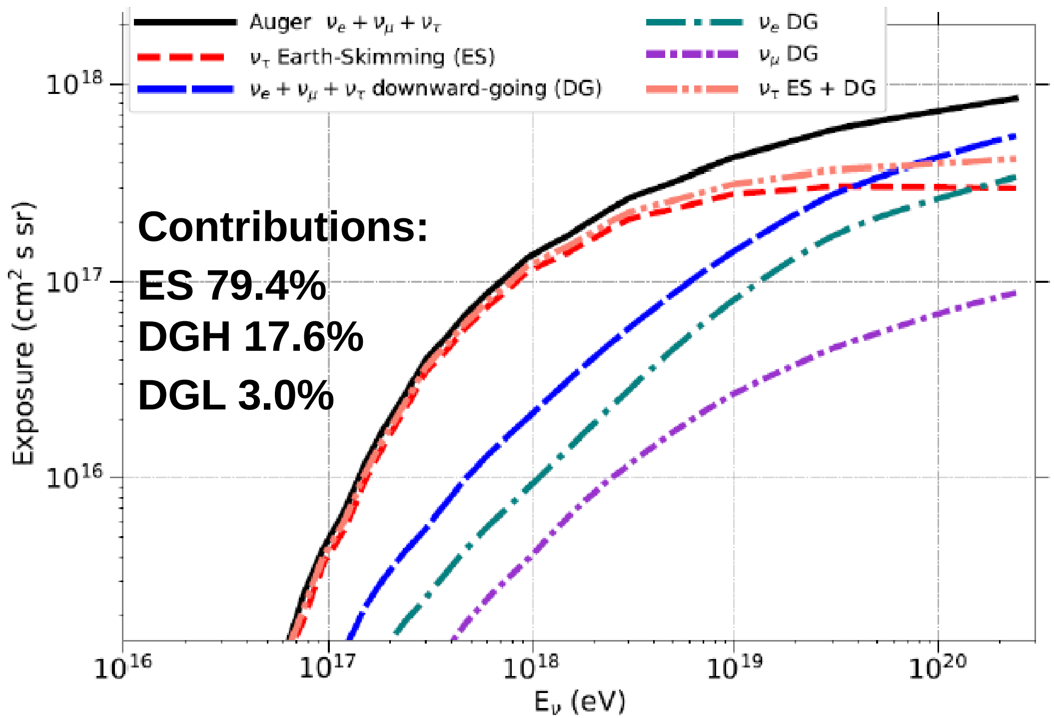






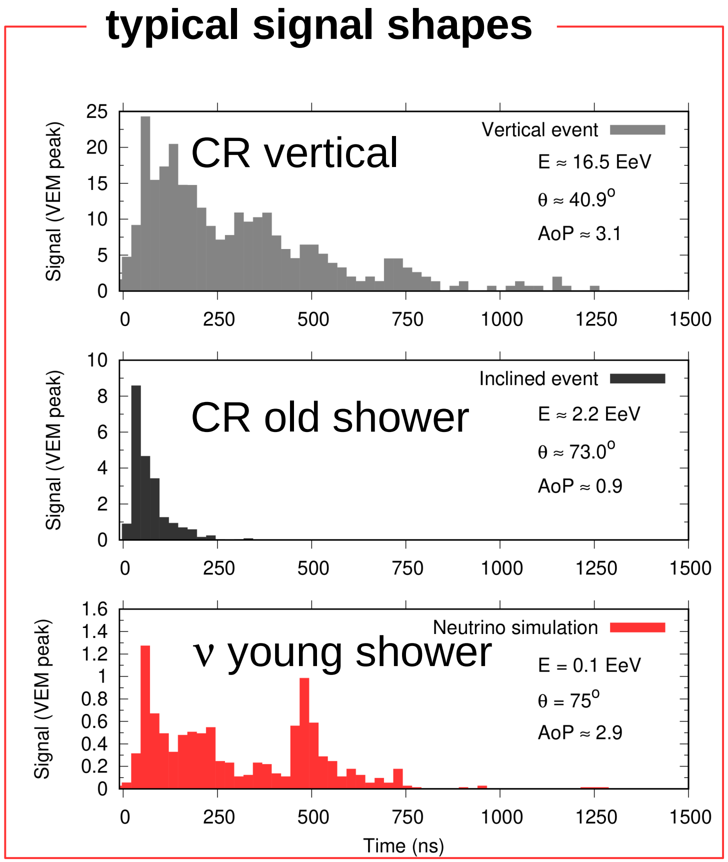


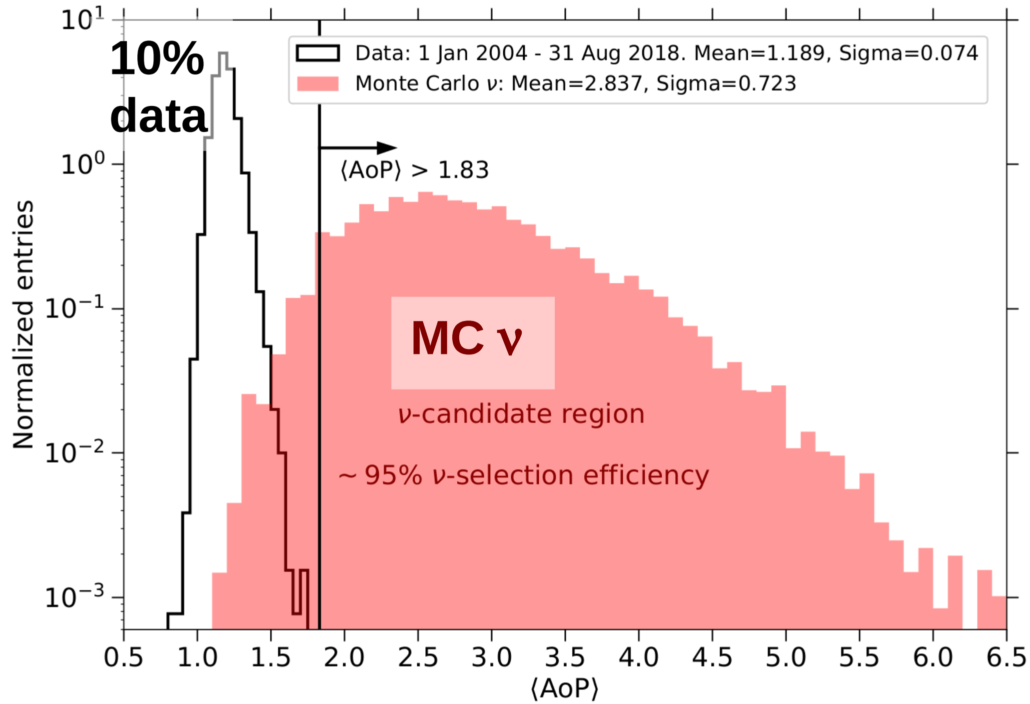
Sensitivity to different channels



ν_τ ES sensitivity dominant

Search for neutrinos with the SD: signature





- Data 2004 – 2018: 14.7 yr of stable operation

→ **bkg expected: <1 event in 50 years**

young shower i.e. with large electromagnetic component

→ inclined event with slow rising and broad signal

→ larger Area-over-Peak (**AoP**)

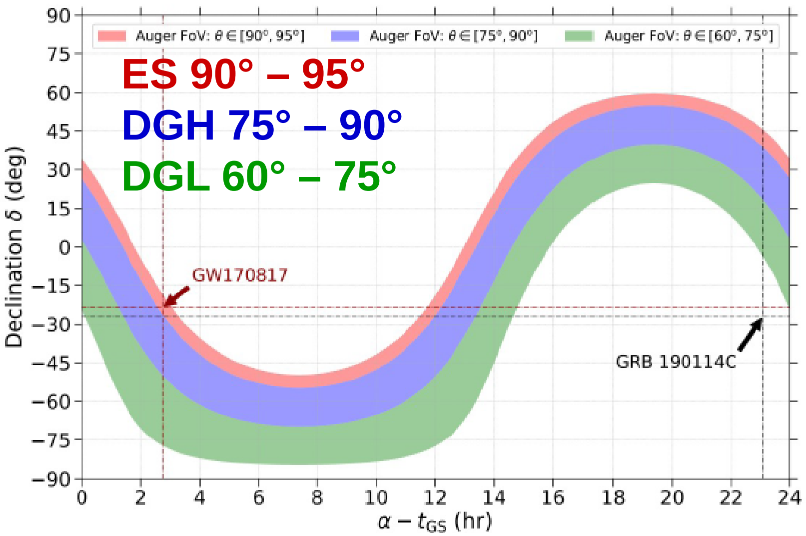
M. Niechciol at this Conf.

NO Candidates found

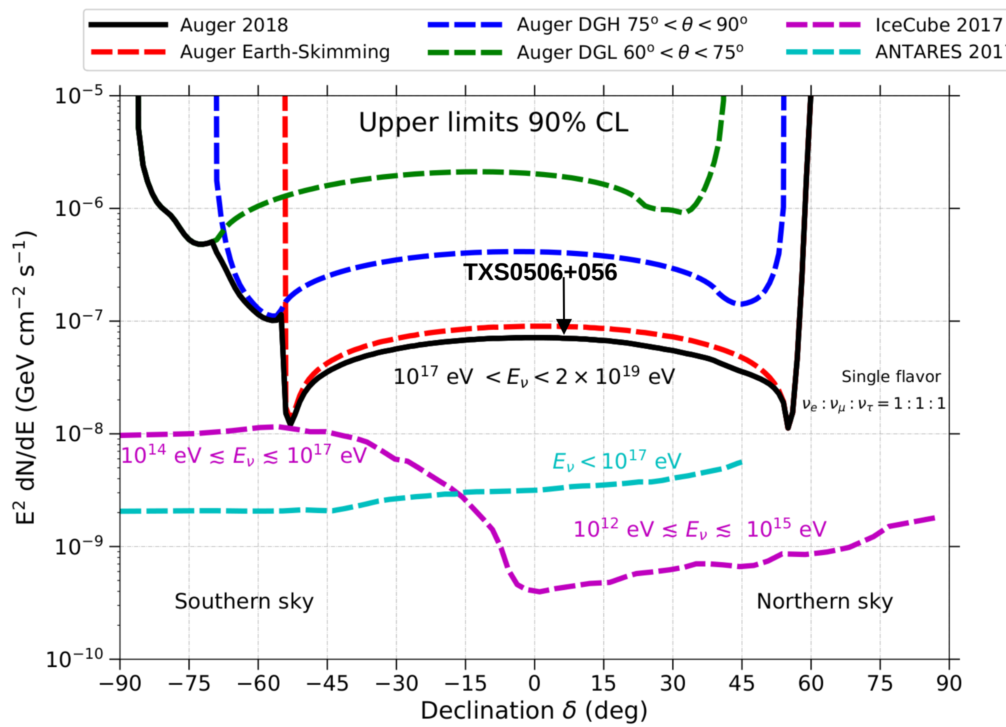
Bounds on cosmogenic neutrino fluxes

tension with models assuming pure proton and spectrum shaped by GZK [up to 6 neutrino expected vs 0 observed]

UHE neutrinos: point sources sensitivity



Pierre Auger Coll., JCAP 11 (2019) 004



→ sensitivity strongly depends on source location and event timing

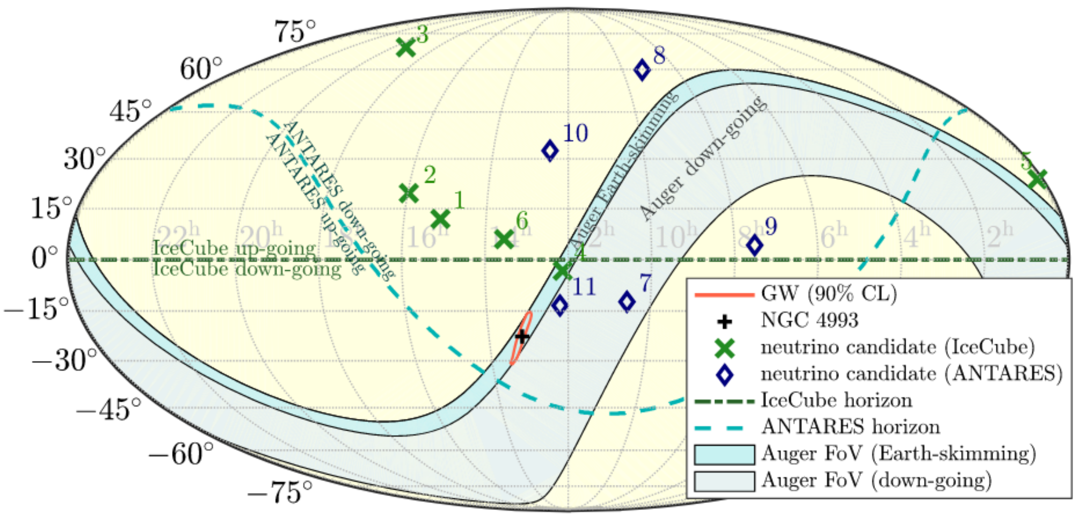
point sources transit through the field of view of each detection channel

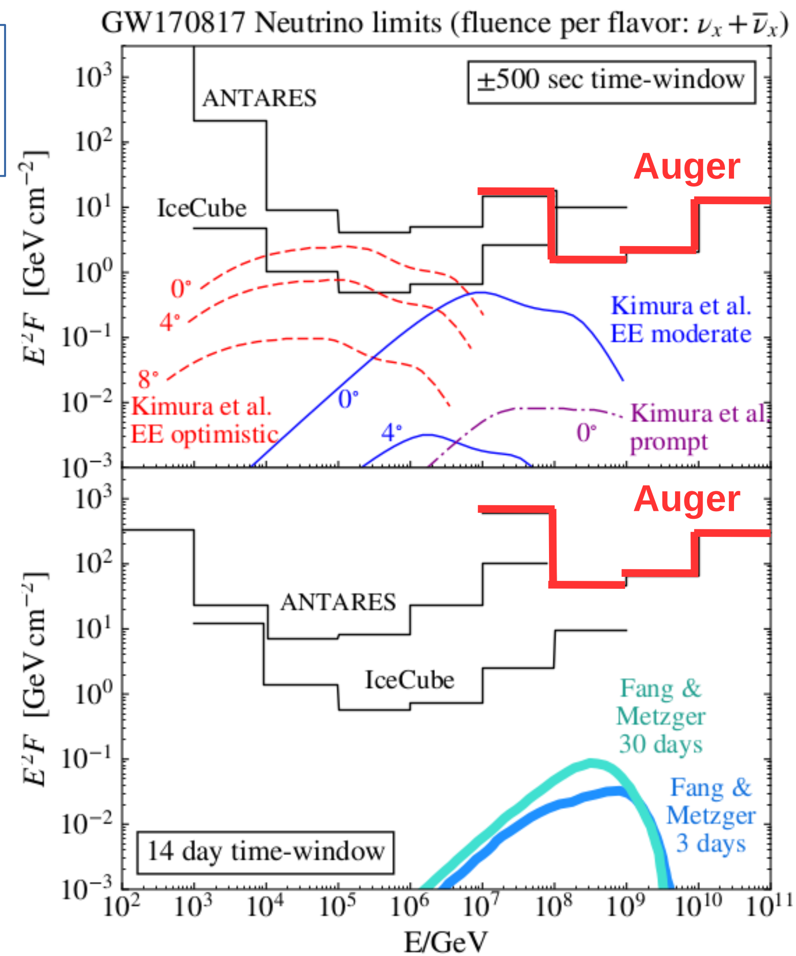
TXS0506+056 declination = 5.7°
Non optimal sensitivity of the source in all channels

→ **good sensitivity in the EeV range in a broad range of declinations**
→ **complementary energy range: $10^{17} \div 2 \cdot 10^{19}$ eV**

Follow-up searches: GW170817

LIGO/Virgo BNS GW170817 & Fermi sGRB 170817A
→ EM counterpart Optical/IR KiloNova AT2017GFO

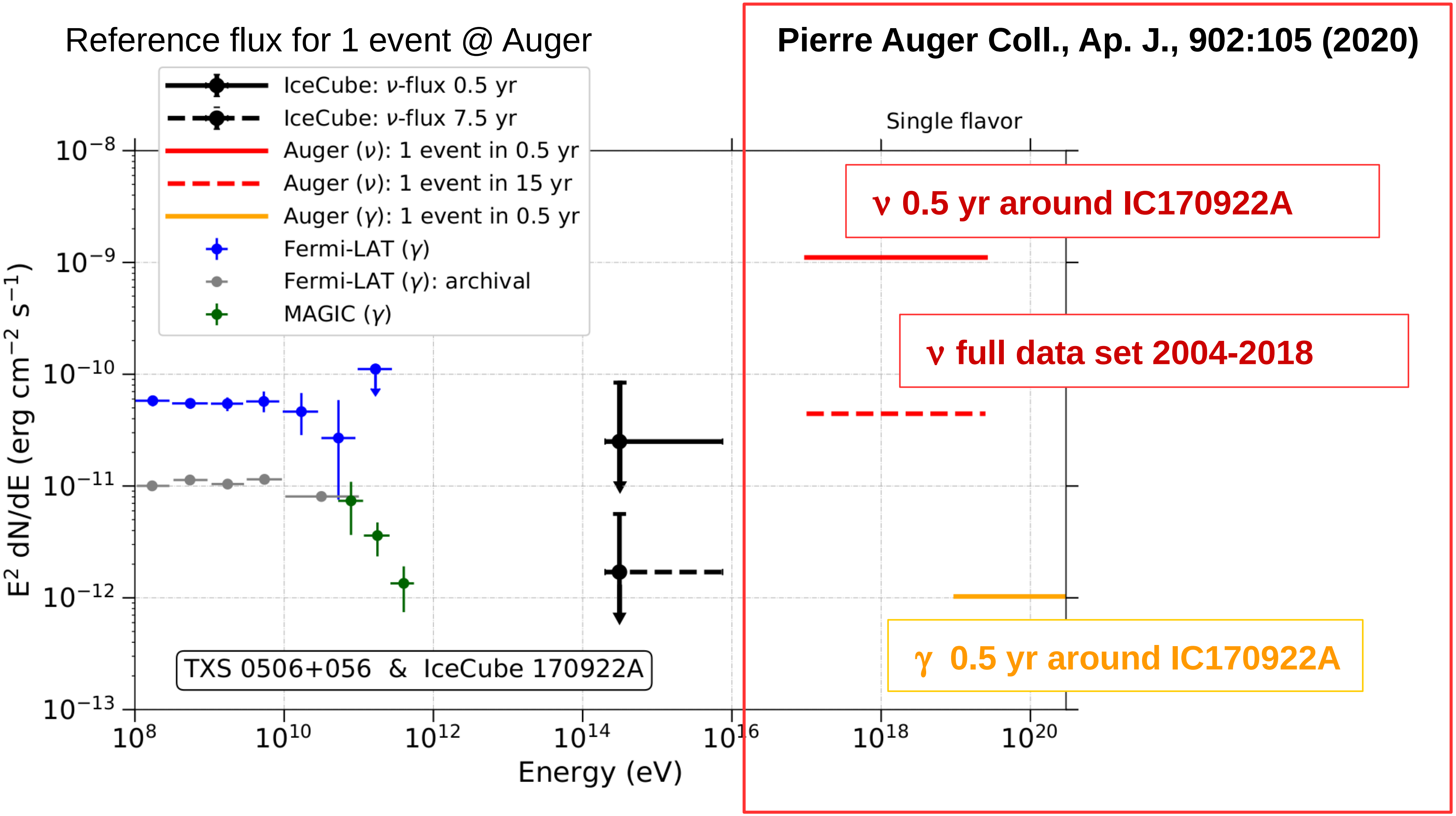




→ excellent visibility of the merger:
90% CL GW event location in FoV of ES channel

→ time dependent exposure leads to substantially lower 14-day neutrino fluence limits wrt to prompt

Auger TXS flux limits



TXS0506+056 declination = 5.7°
Non optimal sensitivity of the source in all channels

PoS(ICRC2021)968, paper in prep.

BBH follow-up (stacked): ν searches

Search for time-directional coincidence with 83 BBH events from LIGO/Virgo.

No candidates found for any of the BBH events inspected

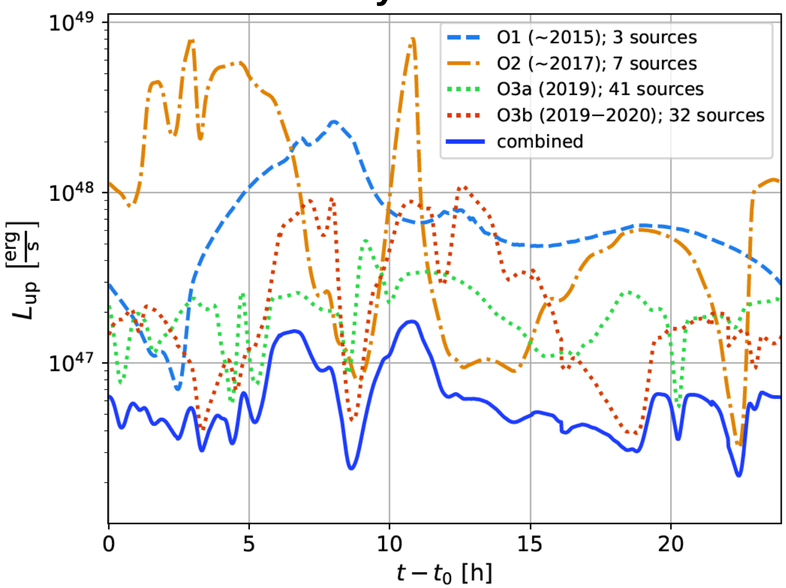
$$L_{\mathrm{up},i} = \frac{N_{\mathrm{up},\nu} \,/\, T}{\sum_{s} P_{\mathrm{BBH},s} \sum_{p \in \Omega_{90}(s)} \rho_{p,s} \mathcal{A}_{p,i} \int_0^\infty \frac{\Pi_{p,s}(r)}{r^2 (1+z(r))} \, \mathrm{d}r}$$

Ω_{90} 90% quantile of the directional PDF (source)

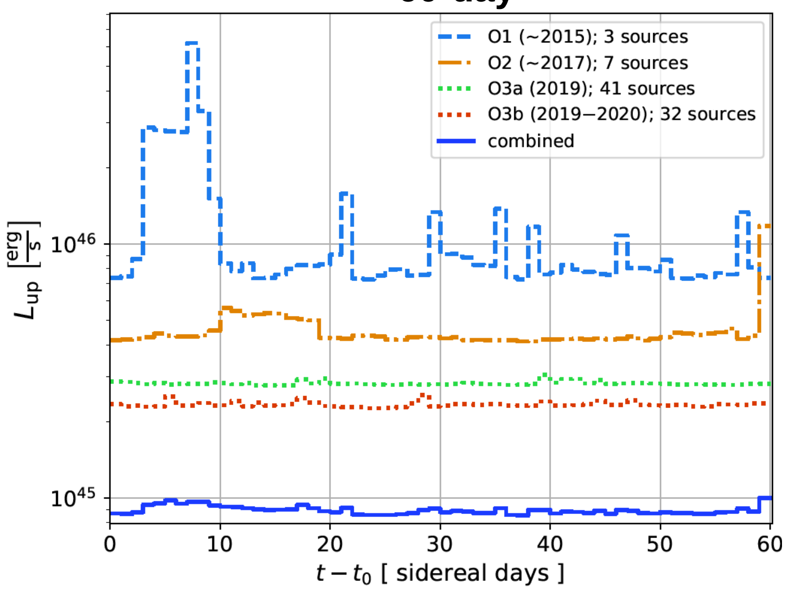
$\Pi_{p,s}$ luminosity distance PDF (pixel,source)

$\mathcal{A}_{p,i}$ exposure (pixel, time bin)

1-day



60-day

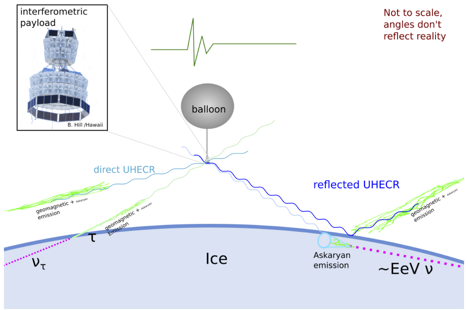


Eν < 6×10^{51} erg → more than 2 orders of magnitude below the radiated GW energy

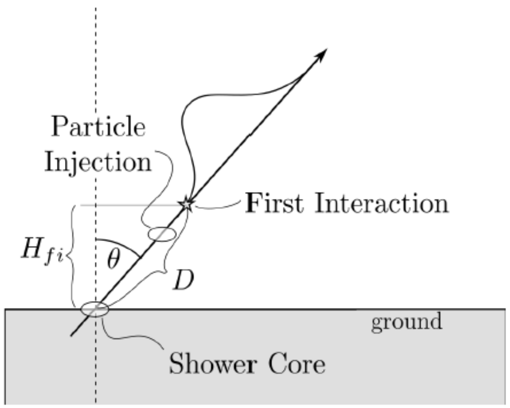
Search for upward-going showers with the FD

Debate triggered after the Observation of the anomalous events by the ANITA experiment

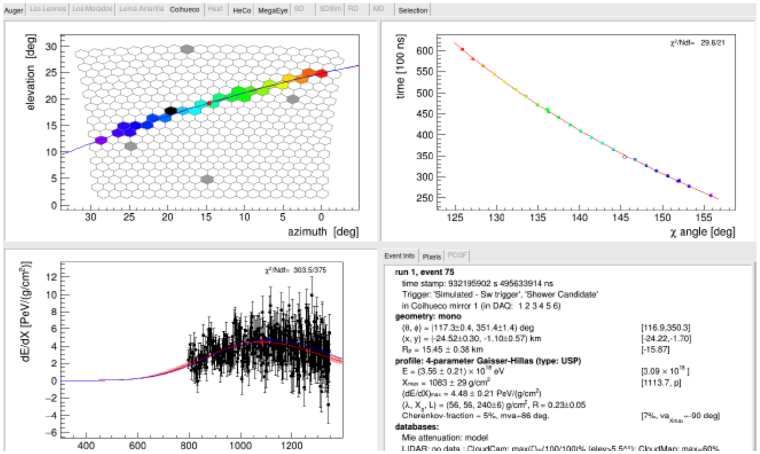
$E_{1,2} \gtrsim 0.2$ EeV, exit angle $\approx 27° \approx 35°$



SIGNAL SIMULATION



Zenith [110°- 180°]
log10 (E/eV) [16.5-18.5]



Quantify the sensitivity of the FD to upward-going showers

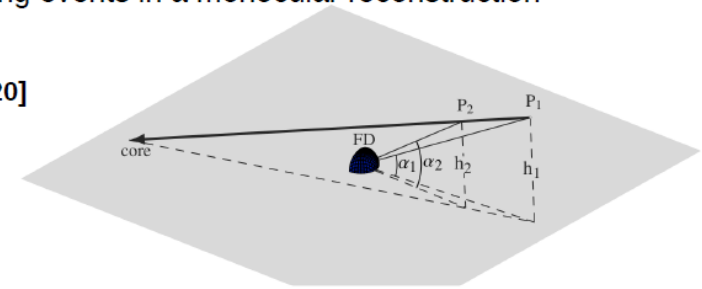
V. Novotny at this Conf.

Use 14 years of FD data (2005-2018) for a dedicated search

BACKGROUND SIMULATION

Downward-going events with specific geometries can mimic upward-going events in a monocular reconstruction

Zenith [0°- 90°]
log10 (E/eV) [17-20]



$\alpha_1 < \alpha_2$
$h_1 > h_2$

Signal from P_1 reaches the FD before the signal from P_2 → downward-going event reconstructed as upward-going

Also events with a core far away from the array can produce background and need to be simulated

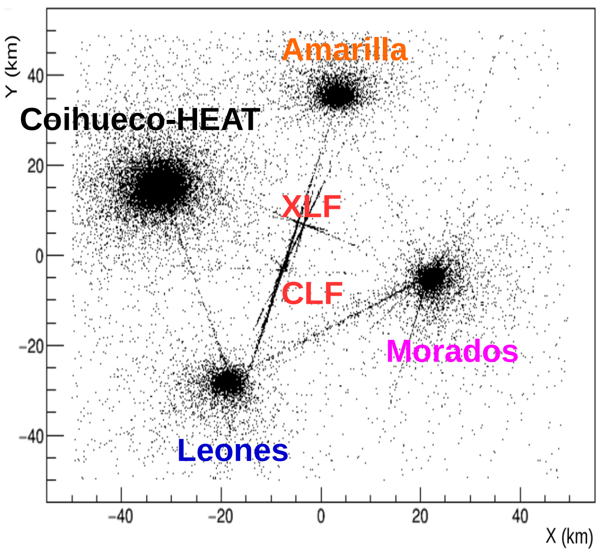
Data cleaning using a burnt data sample

Blind analysis performed using 10% of the FD data from 14 years of FD operation

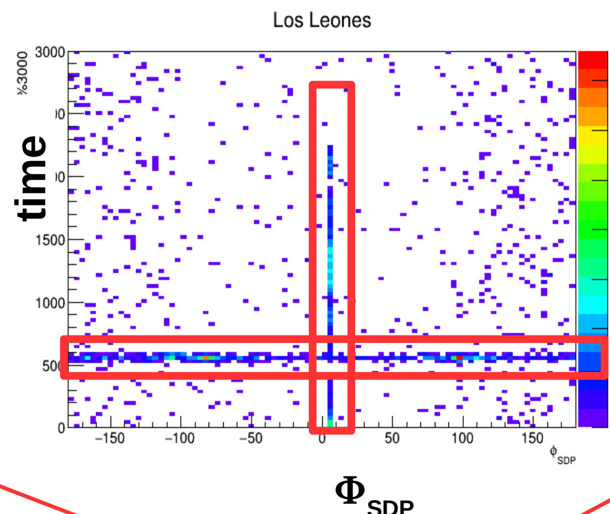
FIRST STEP: remove untagged laser events used to monitor the atmosphere

Lidar shots have a specific frequency of 333 Hz → they pile up in a GPSMicroSecond%3000 histogram

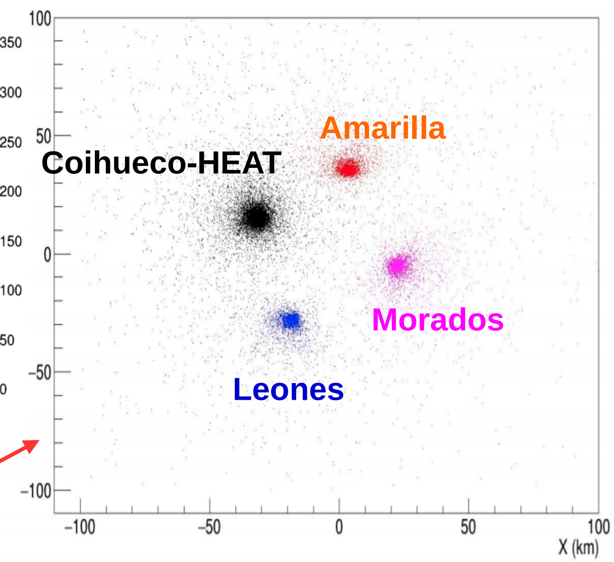
CLF and **XLF** have a known position → the angle Φ_{SDP} that define the intersection of the shower detector plane (SDP) with the ground can be used to identify the associated event



Exit points before cleaning



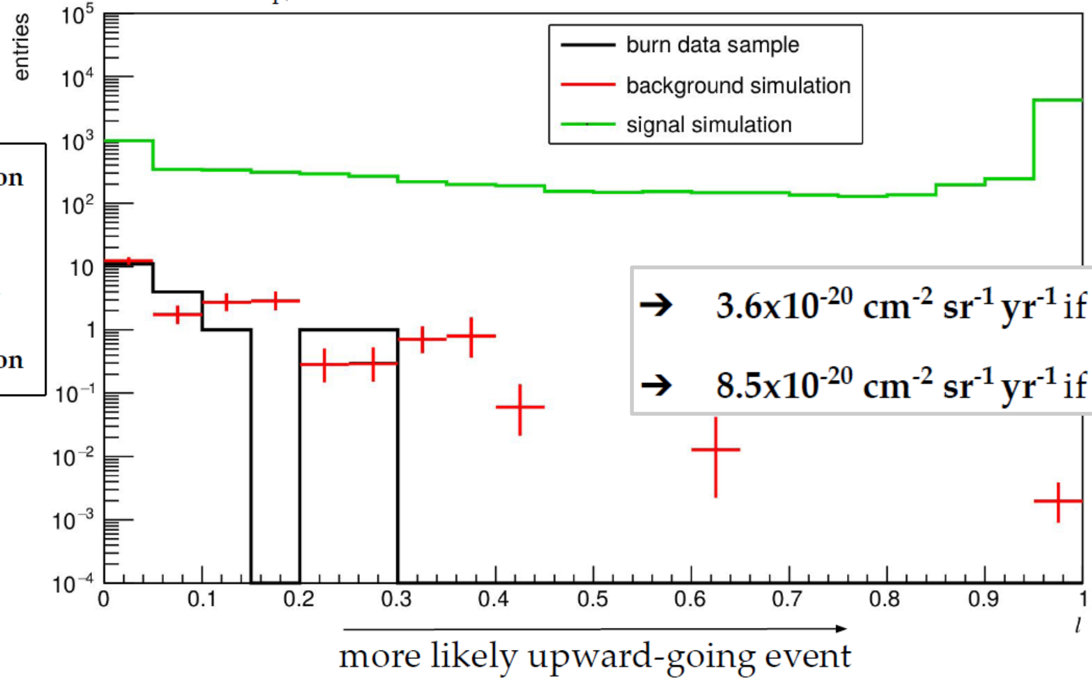
Data driven filtering algorithm



Exit points after cleaning

Upper limits: upward-going showers with the FD

- Variable l = atan(-2log($L_{down}/L_{up,down}$)/50)/(π/2) defined between 0 and 1



background simulation weighted to burn sample → good agreement between burn sample and background simulation

n_{bkg} = 0.45 ± 0.18

1 candidate

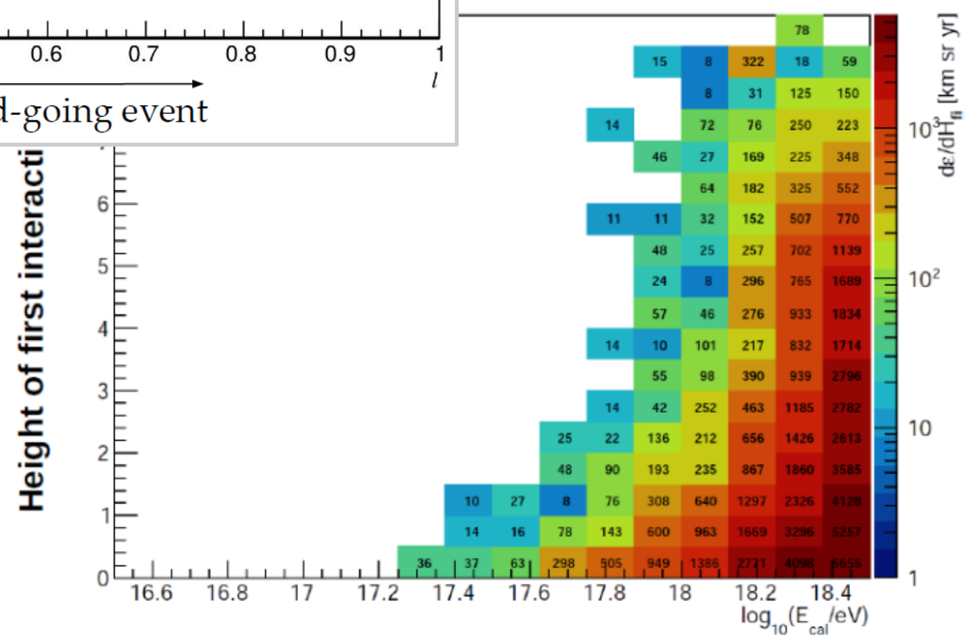
Upper limits

→ 3.6×10^{-20} cm^{-2} sr^{-1} yr^{-1} if exposure is weighted with E^{-1}

→ 8.5×10^{-20} cm^{-2} sr^{-1} yr^{-1} if exposure is weighted with E^{-2}

Detector sensitivity over a wide range of energies and height of first interaction (zenith > 110°)

Useful to test various physics scenarios (taus, BSM)

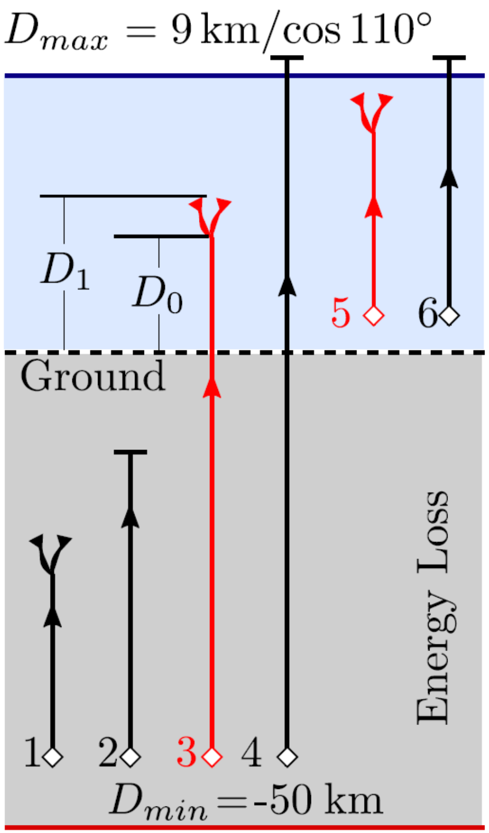


EAS calorimetric energy

PoS(ICRC2021)1140, paper in preparation

A specific case: the tau scenario

PoS (ICRC2021) 1145



16.5< log10(E/eV)<20

110°< zenith<180°

Tau propagation --> NuTauSim
J. Alvarez-Muñiz et al., Phys. Rev. D 97 (2018) 023021

Tau decay → Tauola
M. Chrzaszcz, et al. Comput. Phys. Commun. 232 (2018) 220

main decay branches considered
$e^{+/-}$, $\pi^{+/-}$, π^0, $K^{+/-}$, K^0, contributing to the formation of air showers.

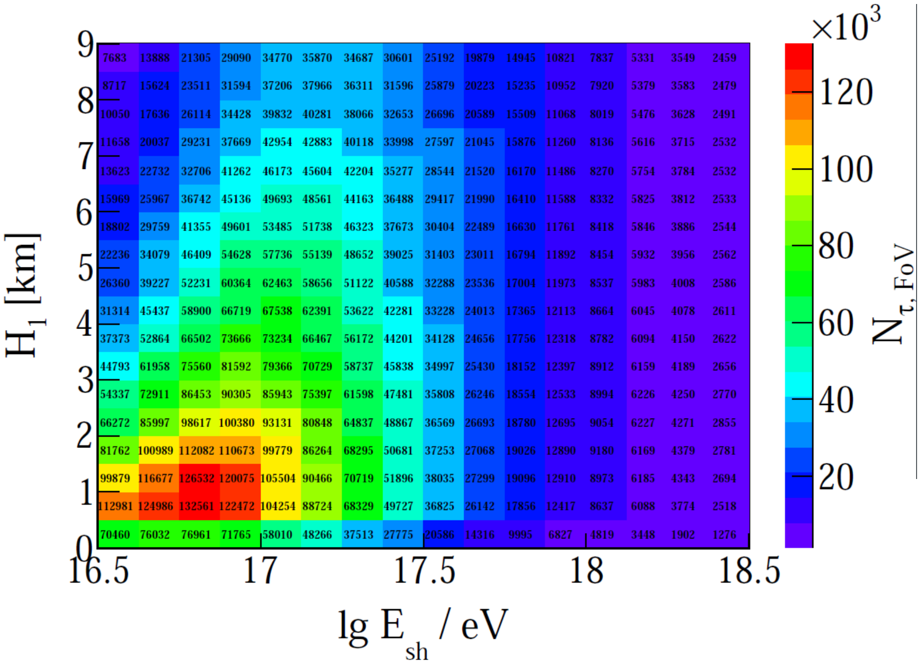
Dmin set by the tau range in standard rock

Dmax set by the FoV of the FD

Channel **3** and **5** are producing air showers within the field of view of FD

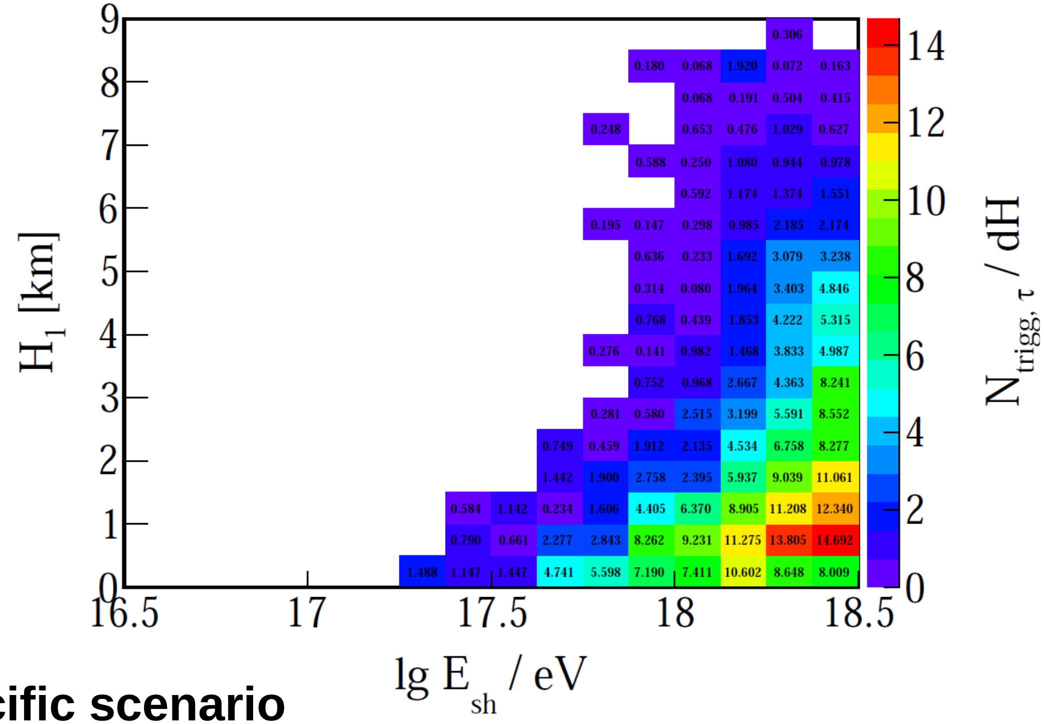
Height of first interaction H1 derived from average of the first interaction depth of each secondary, zenith and atmospheric profile

Folding the FD response with taus in FOV



⊗ FD detector acceptance for generic upwards-going EAS

Observable events



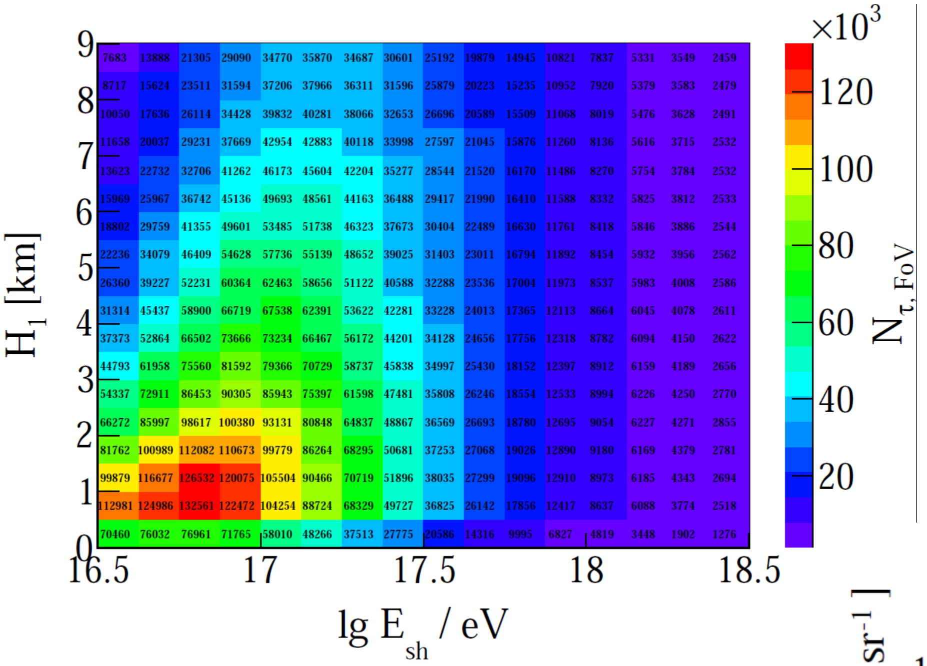
$\mathbf{H_1}$ → height of first interaction

$\mathbf{E_{sh}}$ → energy of the induced shower

Selection criteria and energy range inherited from the generic search

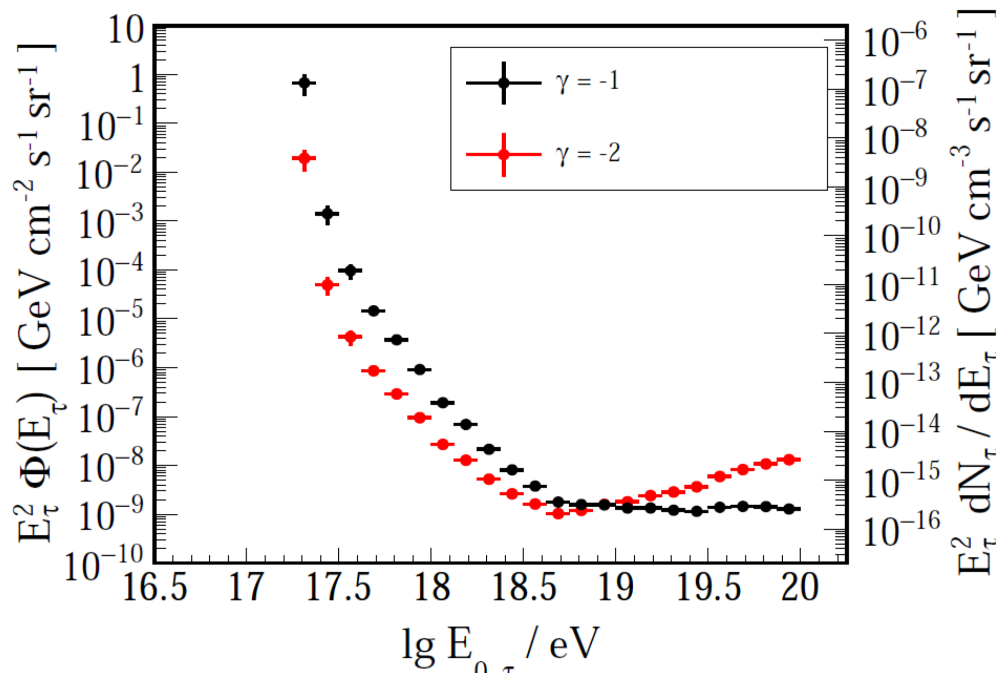
Exposure for this specific scenario

Folding the FD response: flux UL



⊗ FD detector acceptance for generic upwards-going EAS

Differential Upper Limits



H_1 → height of first interaction

E_{sh} → energy of the induced shower

1 event observed, 0.5 expected

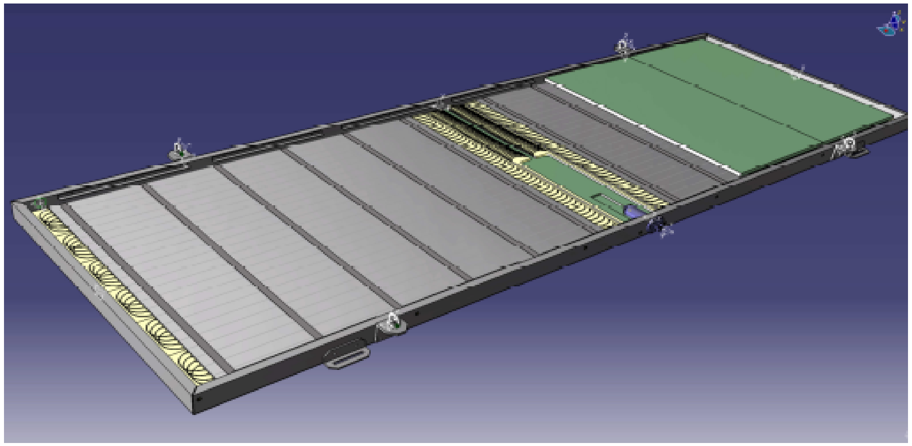
Two injection spectra

$$\Phi_\tau^{95\%}(E_0) = \frac{N_{FC}(E_0)}{\mathcal{E}_\tau(E_0)}$$

Auger upgrade program: Auger Prime

3.8 m^2 (1 cm thick) scintillators on each of the main array station

C. Berat at this Conf.



SSD: scintillators sensitive to the electromagnetic content of the shower

SCIENCE CASE

Origin of the flux suppression, GZK vs. maximum energy scenario, **improve on mass separation**

Search for a flux contribution of protons up to the highest energies at a level of ~ 10%

Study of extensive air showers and hadronic physics $\sqrt{s}$=70 TeV

- Scintillators **SSD**
- Upgraded and faster electronics **UUB** (40 MHz - 120 MHz)
- Extension of the dynamic range with small **sPMT**
- Underground buried **UMD** detectors
- Radio antennas **RD**

Concluding remarks

The Pierre Auger Observatory actively participates in the joint international effort within the framework of multi-messenger astrophysics

- Automatic GW follow-up routine in place

- Sending and receiving alerts to/from Global Coordinate Network (GCN)

- SD Data stream sent to the AMON and Deeper Wider Faster (DWF)

excellent sensitivity to **photons and neutrinos** in the EeV range

→ stringent diffuse limits
→ constraining exotic scenarios and cosmogenic flux predictions
→ coverage of a large fraction of the sky
→ follow-up searches of LIGO/Virgo mergers, ANITA

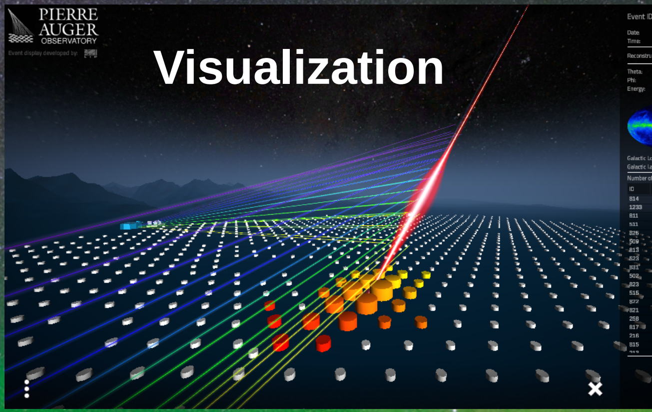
Promoting the interaction with the MM community through the open data portal ⇒ **https://opendata.auger.org**

Pierre Auger Observatory Open Data

February 2021 release

https://opendata.auger.org

doi 10.5281/zenodo.4487613



10% cosmic ray data
100% atmospheric data

Close to raw data and higher level reconstruction

Surface and Fluorescence Detectors

JSON and summary CSV files

Python code for data analysis

Datasets

the released datasets and their complementary data

Visualize

an online look at the released pseudo raw cosmic-ray data

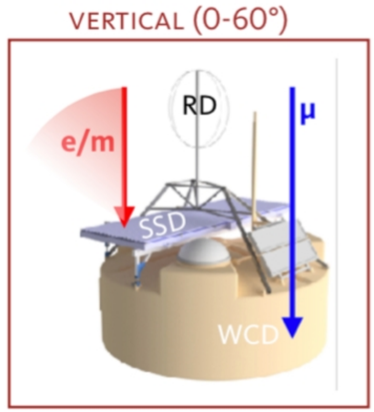
Analyze

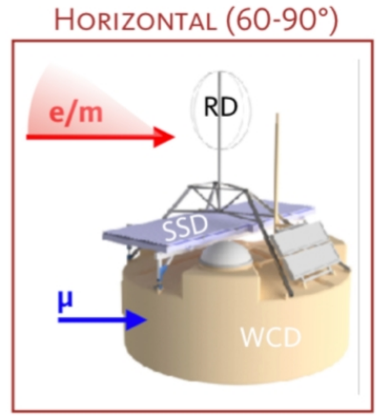
example analysis codes in online python notebooks to run on the datasets

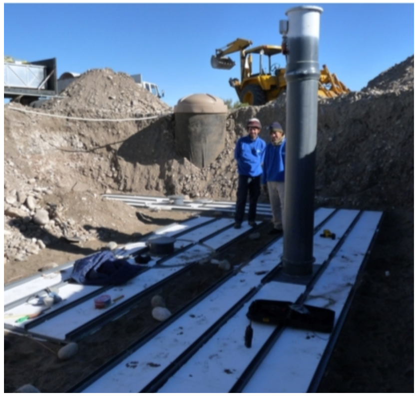
Outreach

a page dedicated to the general public

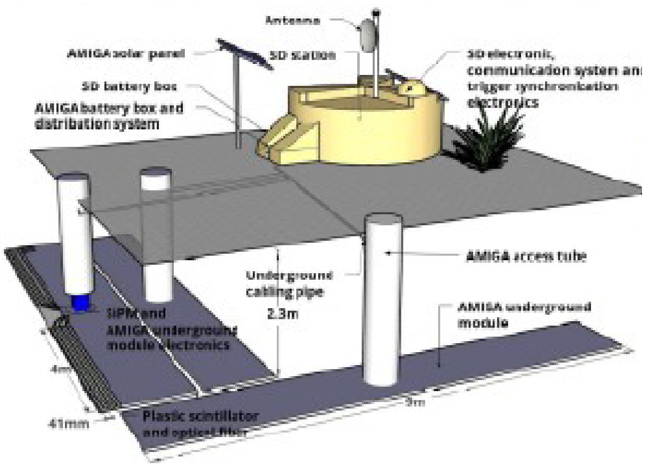
BACKUP SLIDES



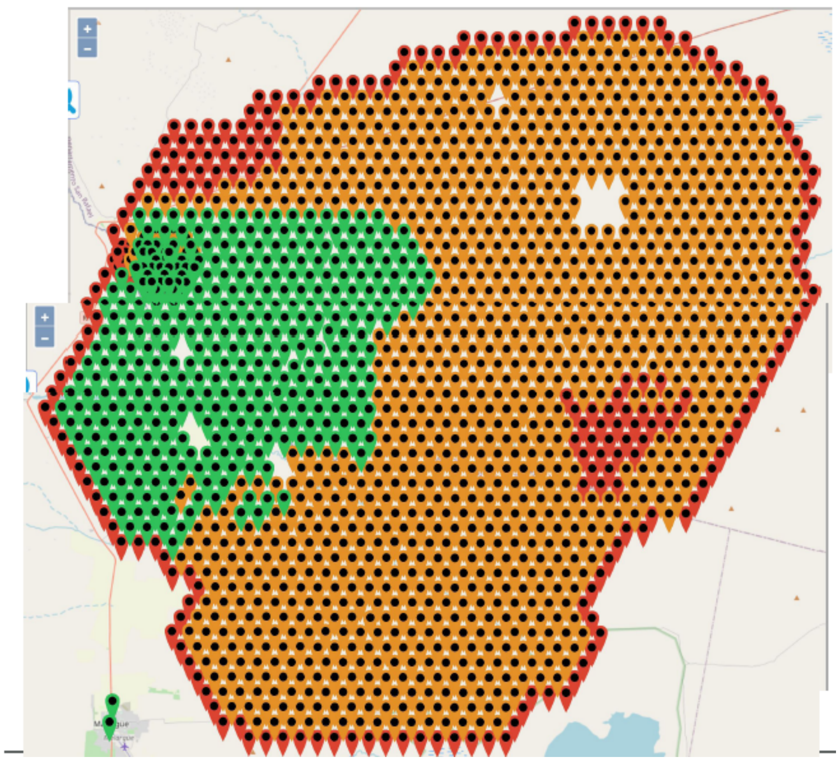




4 positions with 3 UMD each in the field



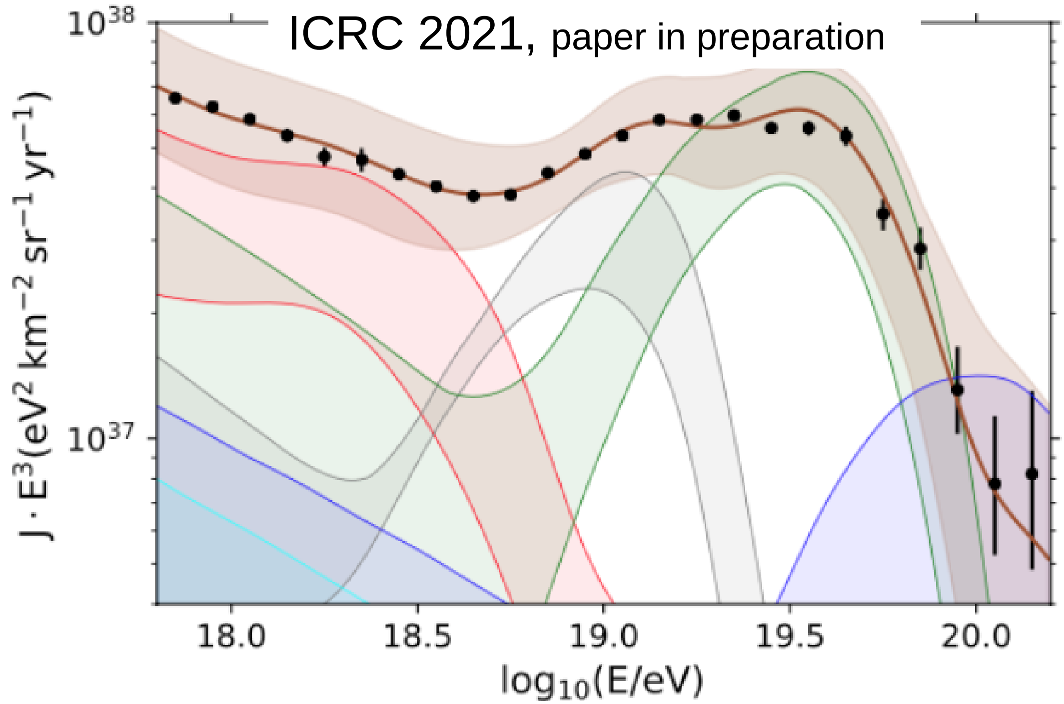
see C. Berat at this Conf.

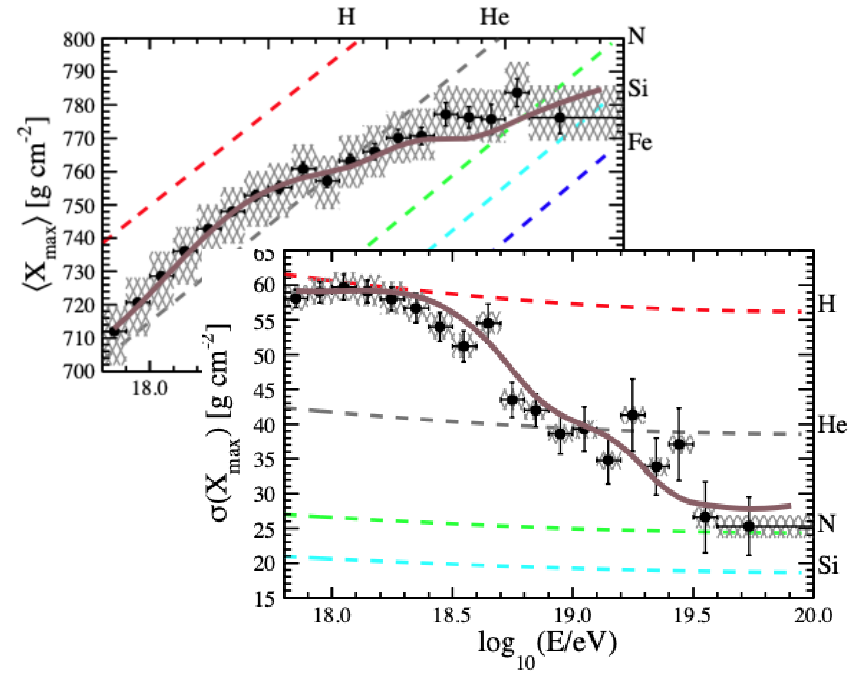


1436 SSD stations deployed

25% of the array equipped with UUB and SSD-PMT and sPMT

Installation completed with UUBs in early 2023





BEST FIT

1) EG: hard HE component
   + soft LE component
2) possible Galactic component (N)

Scenarios compatible within systematics

Dominant experimental systematics

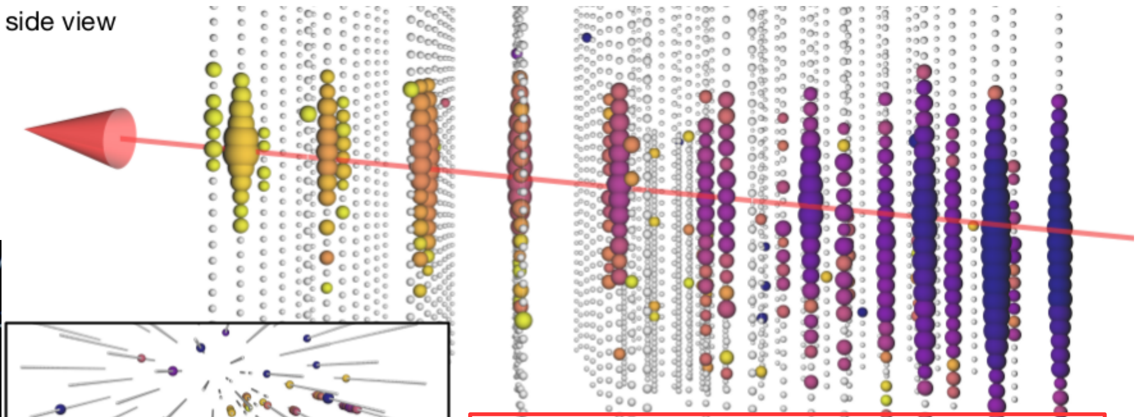
Only propagation, no magnetic fields

	1st scenario		2nd scenario	
Galactic contribution (at Earth)	N+Si		-	
J_0^{gal} [eV^{-1} km^{-2} sr^{-1} yr^{-1}]	$(1.07 \pm 0.06) \cdot 10^{-13}$		-	
$\log_{10}(R_{cut}^{gal}/V)$	17.48 ± 0.02		-	
f_N (%)	93.0		-	
EG components (at the sources)	Low energy	High energy	Low energy	High energy
$\mathcal{L}_0$ [erg Mpc^{-3} yr^{-1}]	$7.28 \cdot 10^{45}$	$4.4 \cdot 10^{44}$	$1.7 \cdot 10^{46}$	$4.5 \cdot 10^{44}$
γ	3.30 ± 0.05	-1.47 ± 0.12	3.49 ± 0.02	-1.98 ± 0.10
$\log_{10}(R_{cut}/V)$	24 (lim.)	18.19 ± 0.02	24 (lim.)	18.16 ± 0.01
I_H (%)	100 (fixed)	0.0	49.87	0.0
I_{He} (%)	-	27.17	10.92	28.60
I_N (%)	-	69.86	36.25	69.05
I_{Si} (%)	-	0.0	0.0	0.0
I_{Fe} (%)	-	2.97	2.96	2.35
D_J (N_J)	49.5 (24)		60.1 (24)	
$D_{X_{max}}$ ($N_{X_{max}}$)	593.8 (329)		554.8 (329)	
D (N)	643.3 (353)		614.9 (353)	

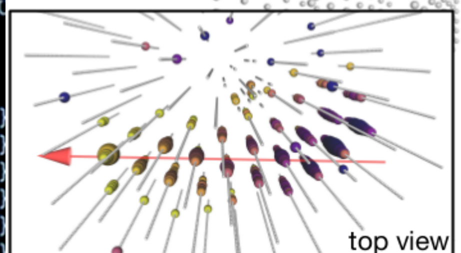
We have a source! TXS0506+056

ICECUBE: Science, Volume 361, Issue 6398, id. eaat1378 (2018)

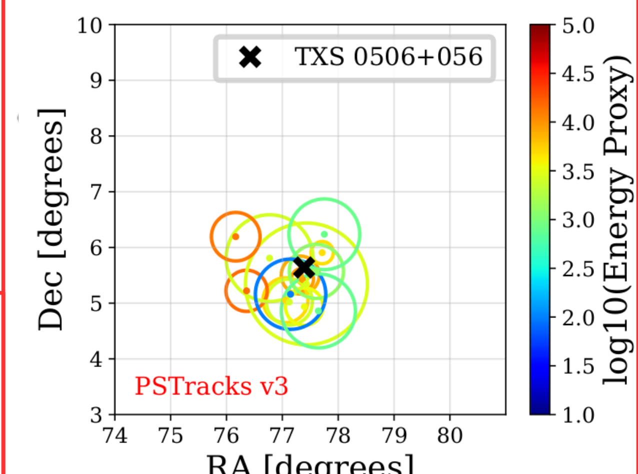
ICECUBE ALERT IC170922A




```
////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 U
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s}
                   77.5221d {+05h 10m 05s}
                   76.6176d {+05h 06m 28s}
SRC_DEC:           +5.7517d {+05d 45' 06"}
                   +5.7732d {+05d 46' 24"}
                   +5.6888d {+05d 41' 20"}
SRC_ERROR:        14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   18018 TJD;    265 DOY;    17/09/22 (yy/mm/dd)
DISCOVERY_TIME:   75270 SOD {20:54:30.43} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
CHARGE:           5784.9552 [pe]
```

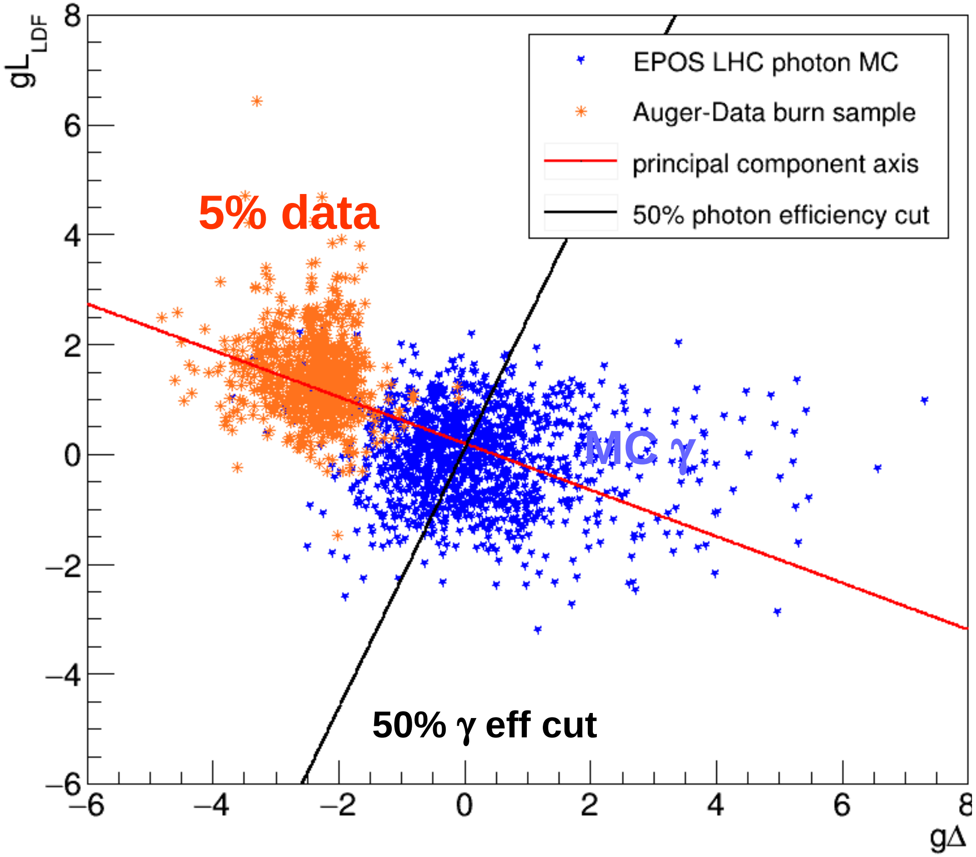


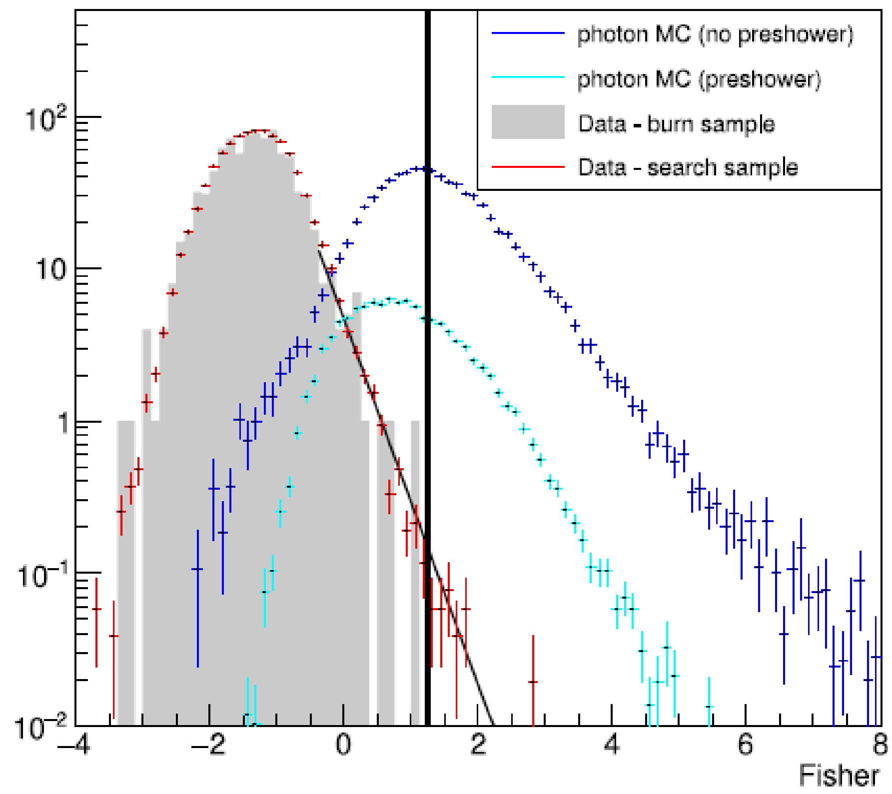
Archival data shows
ν flare in 2014/2015
(~ 3.5 σ level)



https://arxiv.org/abs/2101.09836

SD photon search





Deviation from data <LDF>: $\mathbf{gL_{LDF}}$

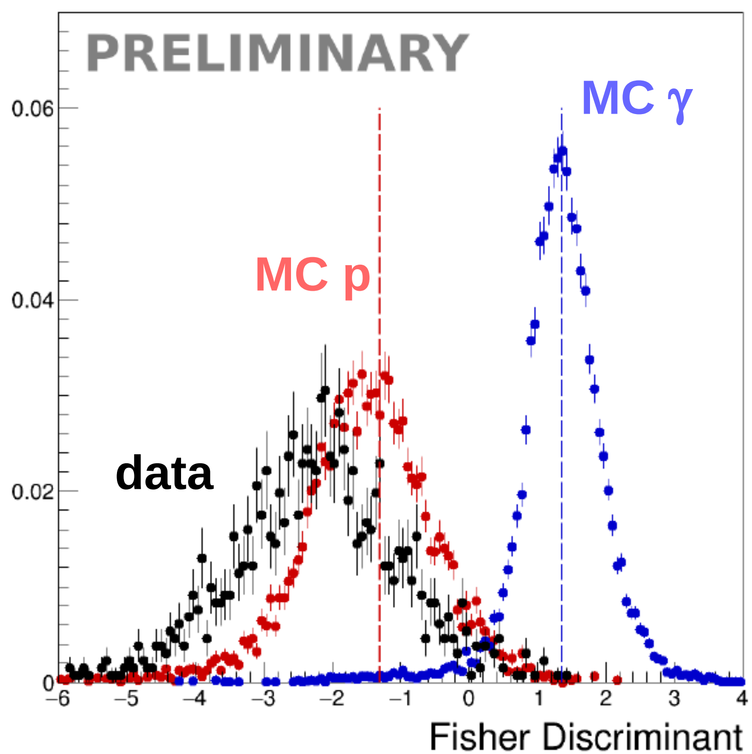
rise-time rel. event-wise quantity: $\mathbf{g_{\Delta}}$

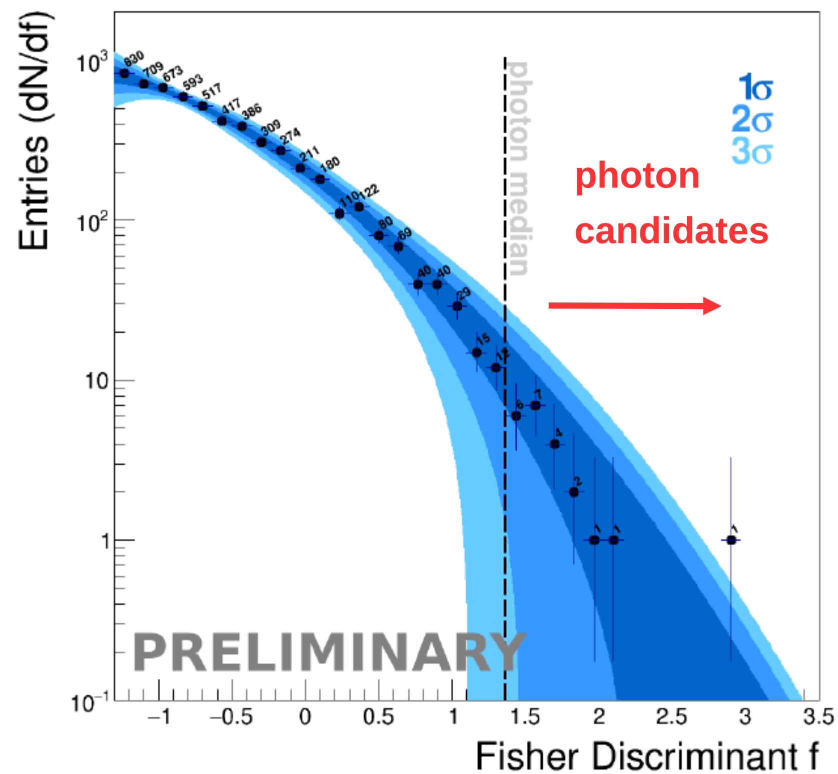
Fisher discriminant

cut at the median of the photon MC no-preshower

Hybrid photon search

Hybrid selection: Fisher response



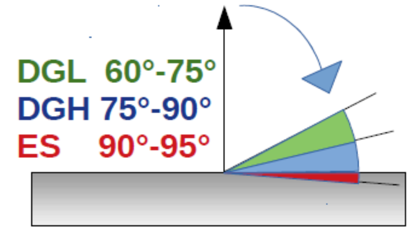


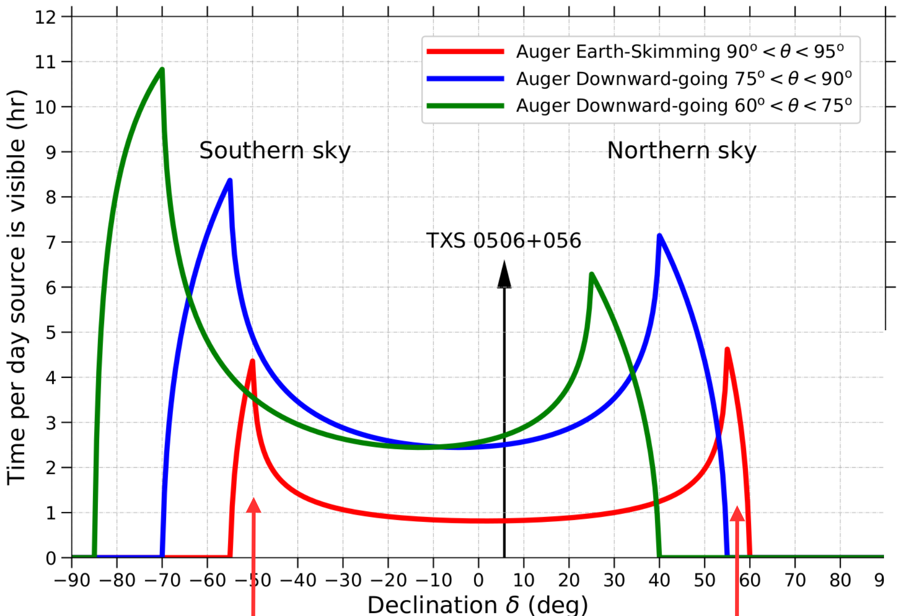
Maximum of shower development: $\mathbf{X}_{max}$

Muon content of the shower (universality): F_{μ}

number of photon candidates
consistent with background

Auger UHE window: TXS0506

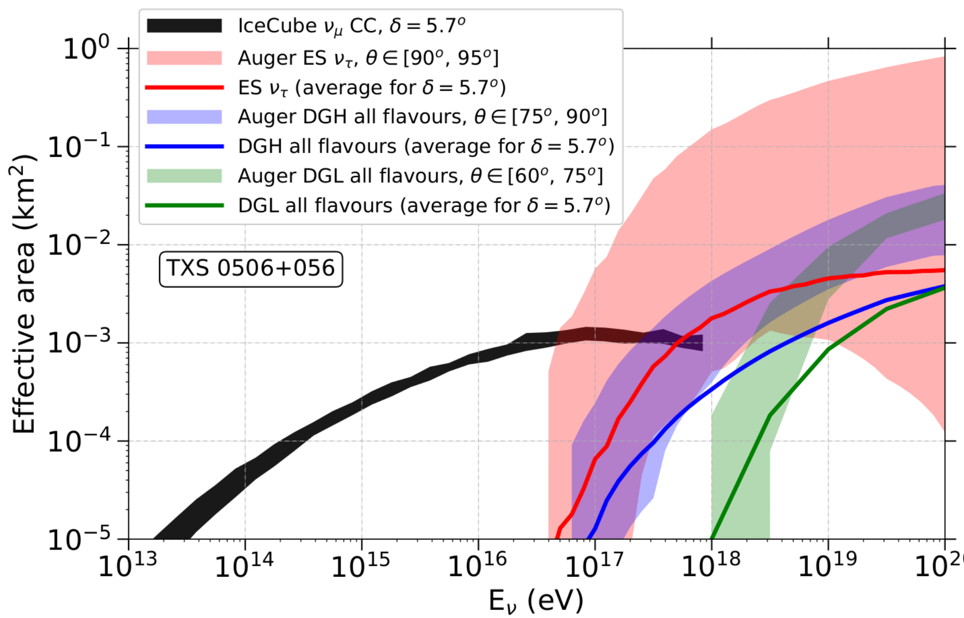




Optimal observation position: source δ in FOV of the Earth-skimming channel (right below the horizon)

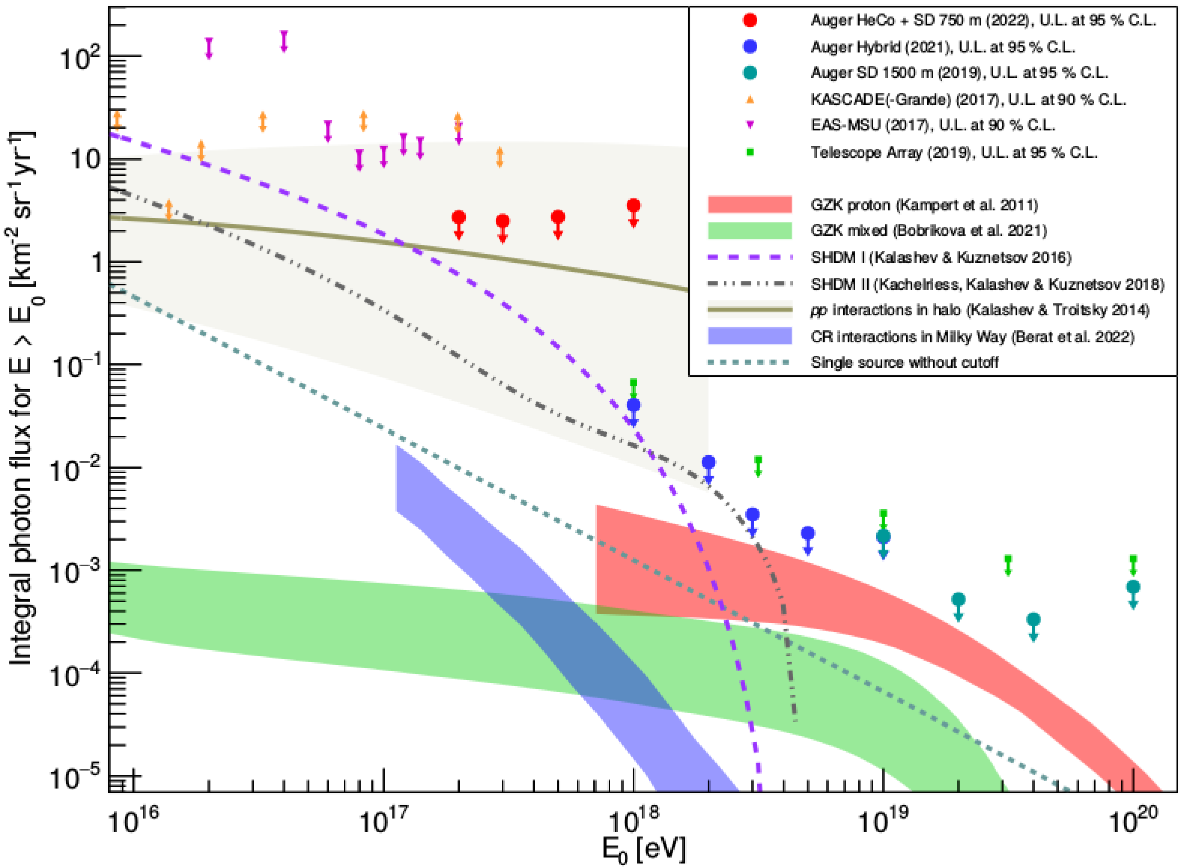
→ complementary to IceCube in the EeV range

TXS0506+056 declination = 5.7°
→ Non optimal sensitivity of the source in all channels



M. Niechciol at this Conf.

Upper limits on diffuse photon flux



Ap. J. 933 (2022)125

Strictest limits at E> 0.2 EeV

11 candidates > 10 EeV (SD)

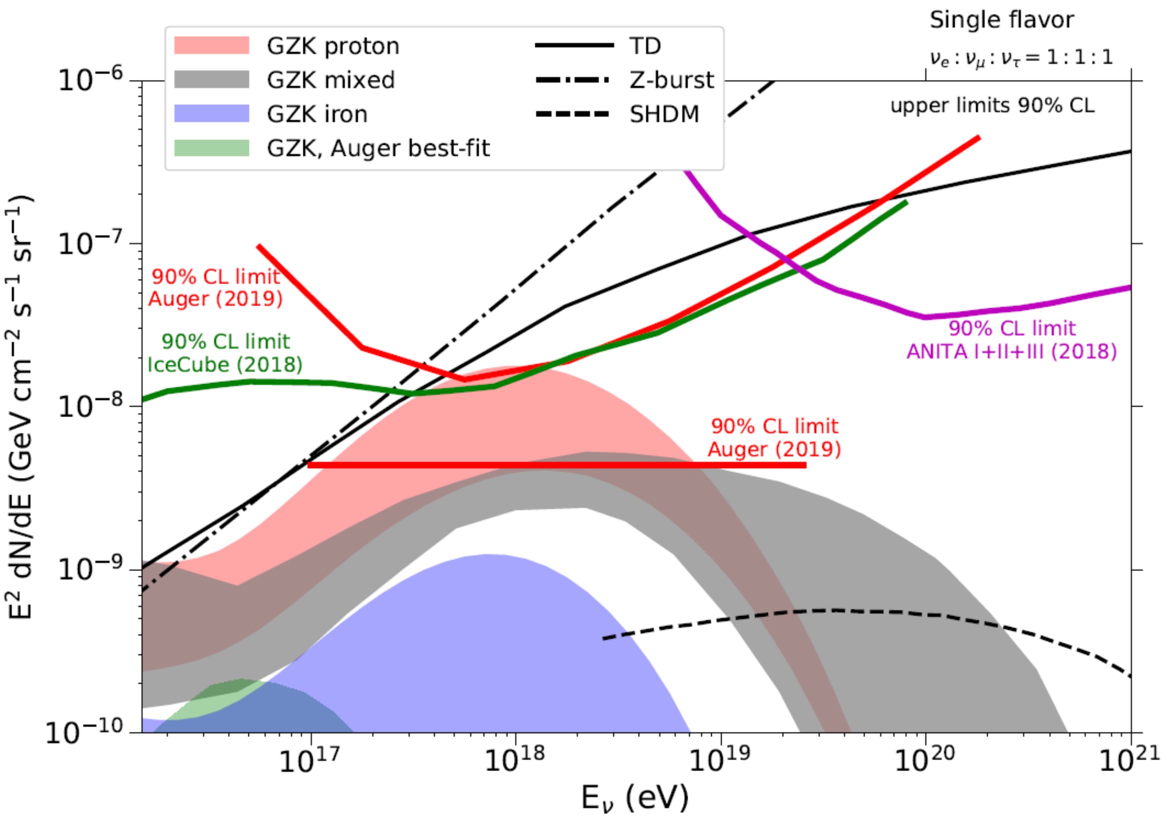
22 candidates > 1 EeV (Hybrid)

- Top-down model disfavored

- CR proton dominated scenario (also the most pessimistic cases) disfavoured
- constraining mass and lifetime of dark matter particles
- Auger Phase II: additional information for better photon/hadron separation or photon discovery

Upper limits on the diffuse neutrino flux

Pierre Auger Coll., JCAP 10 (2019) 022



Identification criteria applied "blindly" to the search data set

NO Candidates found

Bounds on cosmogenic neutrino fluxes

tension with models assuming pure proton and spectrum shaped by GZK [up to 6 neutrino expected vs 0 observed]

Upper limits set assuming dN/dE = k E^{-2}

→ k ∼ 4.4 x 10^{-9} GeV cm^{-2} s^{-1} sr^{-1} [0.1 – 25] EeV

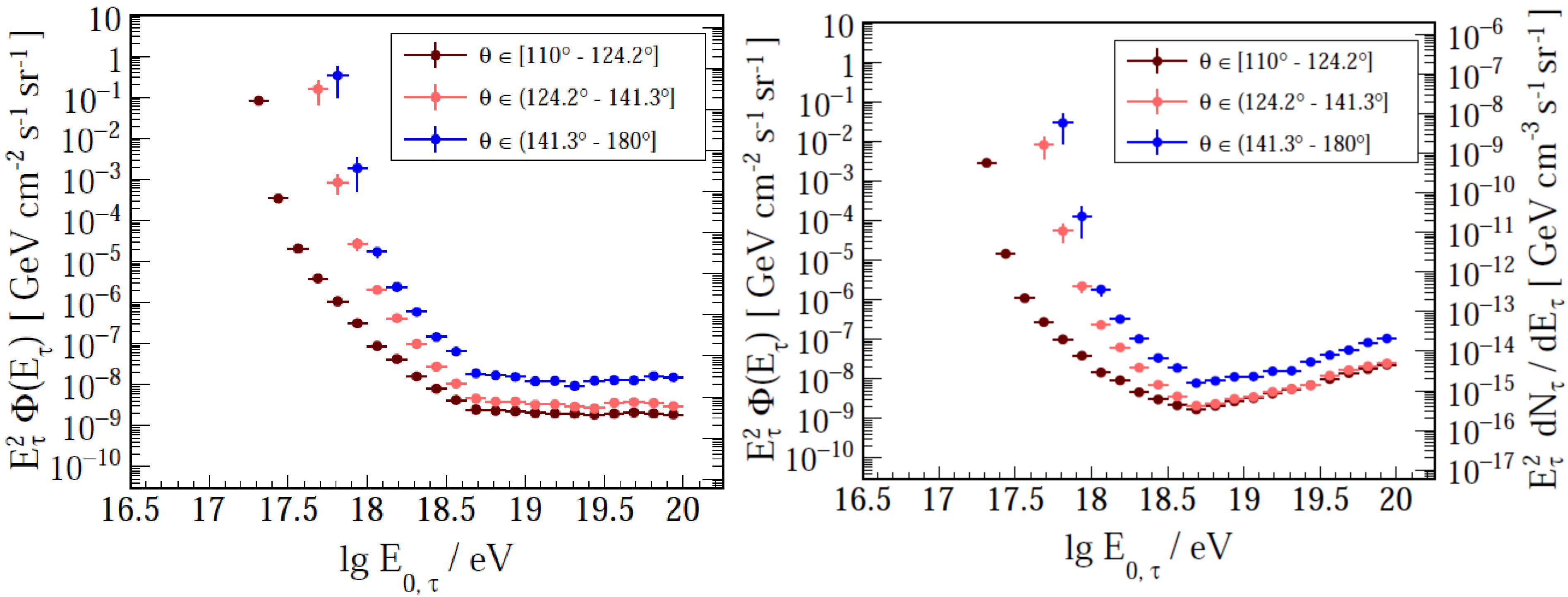
Differential upper limit → maximum sensitivity **in the EeV range**

Differential upper limits

1 event observed, 0.5 expected

$$\Phi_\tau^{95\%}(E_0) = \frac{N_{FC}(E_0)}{\mathcal{E}_\tau(E_0)}$$

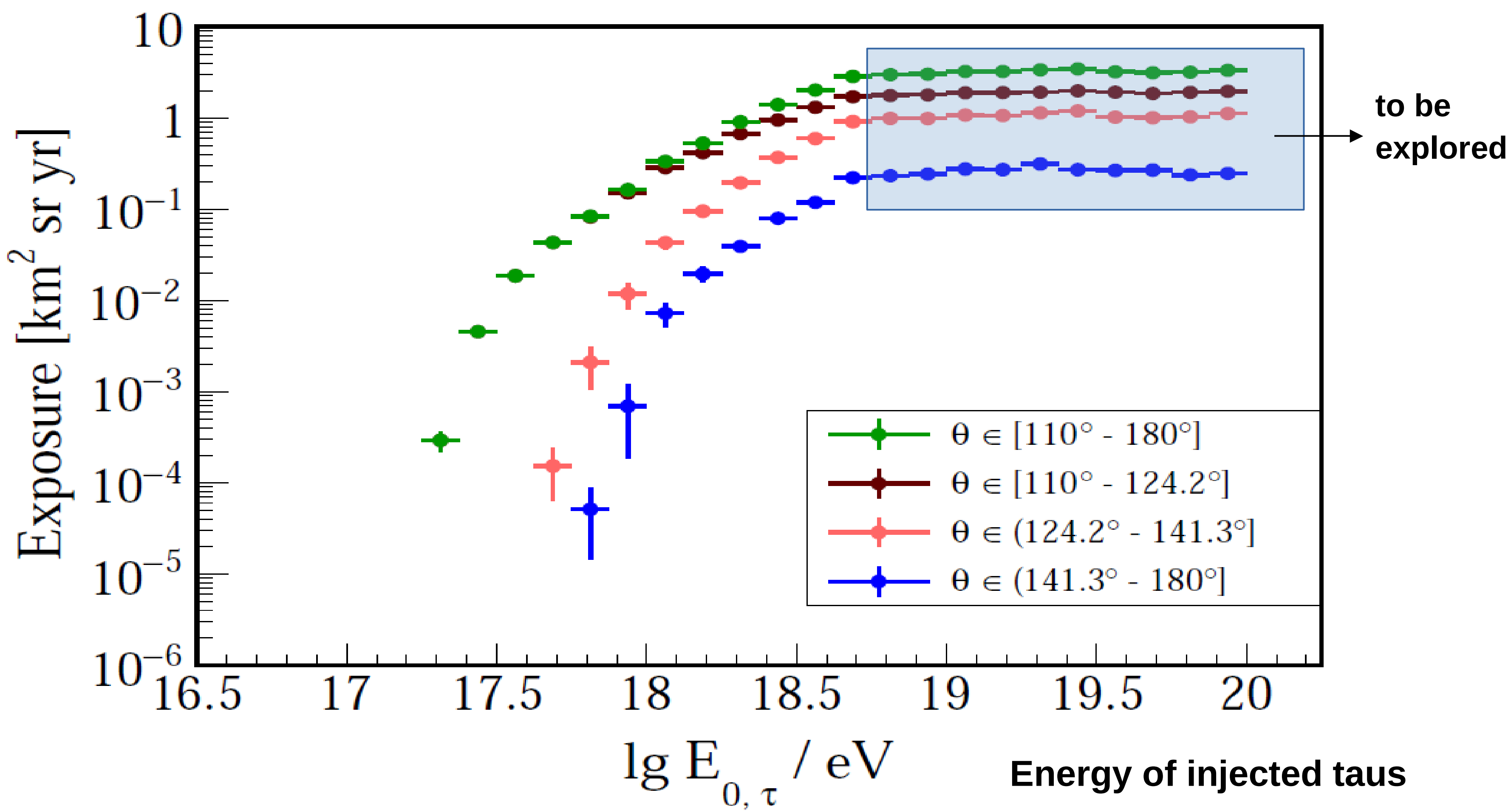
Two injection spectra



(a) $\Phi_\tau \propto E_0^{-1}$ **(b)** $\Phi_\tau \propto E_0^{-2}$

Better limits for inclined events

Exposure for different zenith bands



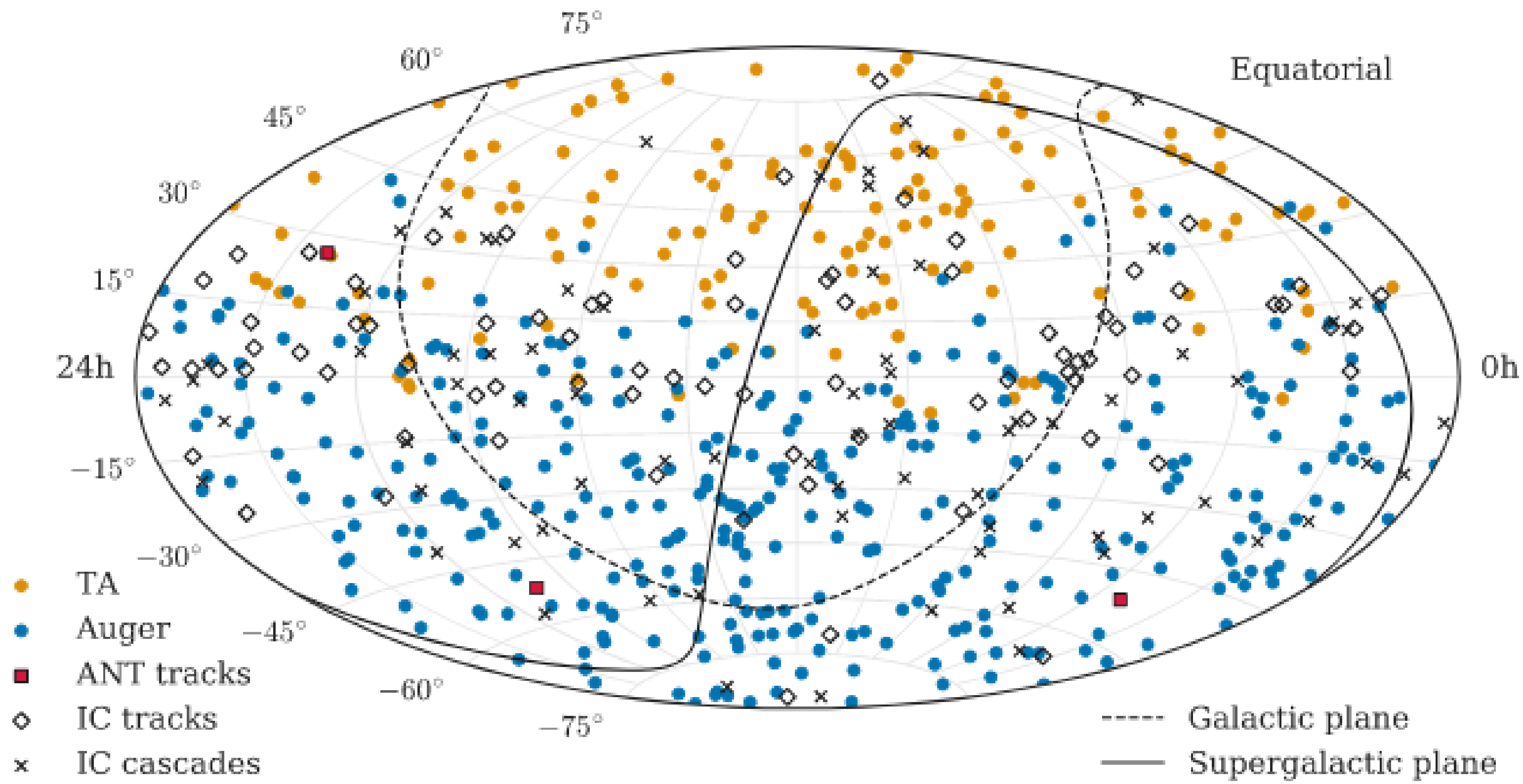
lgE < 18.5 increasing detector efficiency with energy mitigated by the lengthening of tau decay length

lgE > **18.5** FD response not explored yet (flattening is a reasonable assumption)

Joint searches (UHECR and neutrinos)

Antares, **I**ce**C**ube, **A**uger, **T**elescope **A**rray

APJ 934 (2022)164



Three analyses strategies:

– UHECR-neutrino cross-correlation

– Neutrino-stacking correlation with UHECRs

– UHECR-stacking correlation with neutrinos

All compatible with background